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Synergistic Airframe-Propulsion Interactions and Integrations

*A White Paper Prepared by the 1996-1997 Langley
Aeronautics Technical Committee*

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Executive Summary

This white paper documents the work of the NASA Langley Aeronautics Technical Committee from July 1996 through March 1998 and addresses the subject of Synergistic Airframe-Propulsion Interactions and Integrations (SnAPII). It is well known that favorable Propulsion Airframe Integration (PAI) is not only possible but Mach number dependent -- with the largest (currently utilized) benefit occurring at hypersonic speeds. At the higher speeds the lower surface of the airframe actually serves as an external precompression surface for the inlet flow. At the lower supersonic Mach numbers and for the bulk of the commercial civil transport fleet, the benefits of SnAPII have not been as extensively explored. This is due primarily to the separateness of the design process for airframes and propulsion systems, with only unfavorable interactions addressed. The question 'How to design these two systems in such a way that the airframe needs the propulsion and the propulsion needs the airframe?' is the fundamental issue addressed in this paper. Successful solutions to this issue depend on appropriate technology ideas.

In order for a technology (idea) to be applicable it must successfully pass through the two filters of technical and technological. The technical filter addresses the questions: Does it violate any fundamental laws?, Does it work as envisioned?, Can it successfully be demonstrated?; whereas, the technological filter addresses the question: Does it make any sense in the real world?

This paper first details ten technologies which have yet to make it to commercial products (with limited exceptions) and which could be utilized in a synergistic manner. Then these technologies, either alone or in combination, are applied to both a conventional twin-engine transonic-transport and to an unconventional transport, the Blended Wing Body. Lastly, combinations of these technologies are applied to configuration concepts to assess the possibilities of success relative to five of the ten NASA aeronautics goals. These assessments are subjective but point the way in which the applied technologies could work together for some break-through benefits.

The following recommendations are made to continue the work initiated in this document:

(1) Based upon the evaluation presented herein of the potential benefits of applying SnAPII technologies in achieving the Agency's aeronautics goals, we recommend that system studies be initiated to independently assess our findings and perhaps provide the basis for future research in the SnAPII arena to be incorporated into new and existing programs. Those concepts that successfully pass the systems analyses could also be reasonable candidates for small-scale flight testing.

(2) Notwithstanding recommendation number one, it is recommended that all future systems studies in aeronautics consider the application of SnAPII technologies (identified in the first part of this paper), in addition to the technologies currently funded in the aeronautics program for the evaluation of system benefits. This is an appropriate time to re-look at these with advancements in such areas as computational fluid dynamics, materials, manufacturing, as well as new methods to further optimize these technologies. Furthermore, many of these technologies have been adequately tested in wind tunnel settings, but lack flight test verification. Remotely-piloted small-scale flight testing could conceivably be utilized to provide data for these technologies in a flight airframe system to reduce risk and bring them to a higher level of application readiness.

(3) The idea of investigating a combined propulsion/airframe design using a minimum entropy production method may be a good analytical approach, complementing the systems analyses and experimental studies, to exploiting SnAPII technologies. Presently, this method has been applied to only aerodynamic drag-reduction problems, but extending this to SnAPII is a next logical step.

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Preface

This document provides a compendium of technologies that use propulsive power to affect/enhance vehicle aerodynamics. The results generated in the second part of this paper are based on simplified performance equations and conceptual ideas. No effort has been made to optimize or even define a vehicle concept. Instead, it is hoped that a flavor for the potential benefits that may exist from these technologies in synergy has been brought forward. It is the intent of this document to provide the impetus for systems analysis studies in synergistic airframe-propulsion interactions and integrations and, if justified, a complementary research program.

The creation of this document required the concerted efforts of the entire Committee. Listed below are the responsible individuals for particular sections of the paper; the reader is referred to these individuals for more information on a specific topic.

Casey Burley	Circulation Control Wing
Lawrence Huebner	Favorable Shock/Propulsive Surface Interference and Interactions, Revolutionary Vehicle Concepts
John Lamar	Goldschmied Airfoil
Robert McKinley	Thrust Vectoring
Robert Scott	Blown Flaps, Wing-Tip Blowing
Matthew Sexstone	Augmentor/Jet Wing, Evolutionary Vehicle Concepts
William Small	Laminar Flow Control, Natural Laminar Flow, Pneumatic Vortex Control
Abel Torres	Boundary Layer Inlet
Steven Yaros	Wing-Tip Engines/Turbines

I take this opportunity to acknowledge the essential contributions of a number of individuals. Thanks go to Chris Gunther, Dee Bullock, and Bill Kluge for their graphics expertise for the second part of this paper. Thanks also to LATC member emeritus, Scott Asbury, for providing a thorough review of the draft version of this paper. A special thanks to Steven Yaros for serving as the compiling editor of this paper. Receiving text and figures from eight other authors and organizing all of the information into a consistent style was truly a formidable task. Finally, on behalf of the entire committee, I thank the sponsor of this Technical Committee, Dennis Bushnell, NASA Langley Senior Scientist, for his support, encouragement, and constructive comments.

Lawrence Huebner
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1996-97 Langley Aeronautics Technical Committee

Introduction

Historically, the benefits of propulsion-airframe integration (PAI) have been shown to be highly dependent upon the cruise Mach number [ref. 1]. At hypersonic speeds, an airbreathing engine is totally integrated to the airframe. The vehicle forebody serves as an external precompression surface for the inlet flow; the midbody contains the internal inlet, combustor, and internal nozzle; and the aftbody serves as an external expansion surface for the combustion flow. Thus, the complete engine flowpath is made up of the entire vehicle lower surface. At supersonic speeds, it is possible to utilize the flow fields off of engine nacelles to provide favorable interference drag reductions and interference lift. Conversely, the airframe (body or wings) can be used to precompress the flow entering the engine inlets for improved engine performance. However, at subsonic speeds, few appreciable beneficial interactions are being exploited. PAI research and analysis is only used to reduce or eliminate problems or unfavorable interactions. Exploiting PAI at lower speeds may lead to more efficient aircraft and/or entirely new vehicle designs.

In particular, this paper deals with airframe and propulsion technologies and how beneficial interactions and integrations can result in synergistic effects. This led to the titling of the present work as Synergistic Airframe-Propulsion Interactions and Integrations (SnAPII). One basis for this effort can be attributed to a 1966 report by Rethorst, et al. on the elimination of induced drag [ref. 2]. The authors state that, "the most expedient means to eliminate induced drag . . . is to exchange the energy otherwise dissipated in the trailing vortex system into nonuniform energy level flows in the aircraft." They cited three possible methods for achieving this, namely, by exchanging this energy to (1) a lower energy level system in the boundary layer, converting vorticity or angular velocity into pressure on the back of the wing, (2) an extended uniform energy level system to spread the vorticity over a larger wake, and (3) a higher energy level system to integrate the vorticity with the propulsion system to recover trailing-edge vortex energy as pressure. It is the last of these methods that provides the connection with the present study.

Induced drag minimization is an inherent part of aircraft design and is carried out not only by experimental methods, but by using several different analyses, which usually involve simplifications such as a planar wake assumption. Greene [ref. 3] has approached this problem from a different direction, basing his "viscous lifting line" method on the principle of minimum entropy production. He has analyzed wing configurations with tip extensions, winglets, and in-plane wing sweep, with and without a constraint on wing-root bending moment. The approximate closed-form solutions obtained by Greene could possibly be extended to numerical optimizations including propulsive effects and their interaction with the external aerodynamic flow. Such an approach could also include structural and geometric constraints and might be valuable in the analyses of SnAPII configurations.

Some of the technologies that were studied use the additional energy added to the airplane system via the combustion of fuel (stored chemical energy) in the propulsion system in a way that provides beneficial airframe-propulsion interaction. Other technologies use more passive methods of extracting energy, such as wing-tip turbines. It is the intent of this paper to unbound the typical constraints imposed on basic performance metrics, such as high lift, cruise efficiency, and maneuver, by exploiting these technologies in a SnAPII way. One process for doing this is to address the full degrees of freedom for certain aspects of aircraft design. These degrees of freedom include: the type of propulsion system utilized; engine geometric design and placement; interactions between the engine(s) and the body, engine(s) and wings, engine(s) and empennage, and engine(s) with other engine(s); engine inlet ducting and nozzle shaping; and interactions of engine-generated flow phenomena.

Combined with the potential technology applications of PAI, one must also address the current airplane design philosophy to identify an important perspective on the realistic impact of this effort. New technologies and airplane designs are currently guided by "the economics of air travel." [ref. 4] They must meet the needs of the customer, and focus on utilization, maintenance, and airplane price. The

technologies for new airplane designs need to be focused on solving real problems that make good economic sense for those that buy airplanes. Rubbert [ref. 5] adds that new strategy is market- or customer-driven, not technology driven. Furthermore, he states that "the driving factor is economic performance, the ability of the airplane to do its job at less overall cost, with the utmost in safety and reliability."

In order to have a good technical idea applied to a new aircraft, it must pass through two filters. The first filter addresses the questions: Does it violate any fundamental laws?, Does it work as envisioned?, Can it be successfully demonstrated?; whereas the second filter addresses real world concerns, such as economics [ref. 6], regulations, and the various operational '-ilities' [ref. 1]. The technology ideas discussed subsequently make an effort to address the status of readiness for aircraft application.

The objectives of this white paper are to present a concise summary of available technologies that provide synergistic interactions and integrations of the propulsion and airframe systems. This includes brief descriptions of the concepts, current and/or past utilization, technology benefits, and issues for incorporating them into aircraft design. Following this, the paper describes the potential application of these technologies, including quantification of benefits, where possible. The paper will conclude with a summarization of the salient points of the paper and recommendations for future research. It is the intent of the paper to address the future research recommendations with respect to the latest report from NASA Headquarters on aeronautics [ref. 7]. Where appropriate, we will take into account the goals underlying the three pillars of aeronautics and space transportation success. These pillars are: (1) to ensure continued U. S. leadership in the global aircraft market through safer, cleaner, quieter, and more affordable air travel, (2) to revolutionize air travel and the way in which aircraft are designed, built, and operated, and (3) to unleash the commercial potential of space and greatly expand space research and exploration. In support of these pillars are ten goals. They are to: improve safety by reducing aircraft accident rates, reducing emissions and noise, increase air travel capacity while maintaining safety, reducing the cost of air travel, reducing intercontinental travel time, increase production of general aviation aircraft, provide next-generation design tools and experimental aircraft to increase the confidence in future aircraft design, and reduce payload cost to orbit by one, then two, orders of magnitude.

References.

1. Bushnell, Dennis M.: "Aerodynamics/Aeronautics in an Open Thermodynamic System." Presented to the Langley Aeronautics Technical Committee, July 11, 1996.
2. Rethorst, Scott; Saffman, Philip; and Fujita, Toshio: Induced Drag Elimination on Subsonic Aircraft. U.S. Air Force, AFFDL-TR-66-115, December 1966.
3. Greene, George C.: An Entropy Method for Induced Drag Minimization. SAE Technical Paper Series 892344. Aerospace Technology Conference and Exposition, Anaheim, CA, September 1989.
4. Condit, Philip M.: Performance, Process, and Value: Commercial Aircraft Design in the 21st Century. 1996 Wright Brothers Lectureship in Aeronautics, presented at the World Aviation Congress and Exposition, Los Angeles, California, October 22, 1996.
5. Rubbert, Paul E.: CFD and the Changing World of Airplane Design. ICAS-94-0.2, pp. LVII-LXXXIII, Copyright © 1994 by ICAS and AIAA.
6. Bushnell, Dennis M.: "Application Frontiers of 'Designer Fluid Mechanics,' Visions vs. Reality." Presented to the Langley Aeronautics Technical Committee, November 1, 1996.
7. NASA Office of Aeronautics and Space Transportation Technology: Aeronautics & Space Transportation Technology: Three Pillars for Success. March 1997.

Bibliography.

Ferri, Antonio, Lecture Series Director: Airframe Engine Integration. AGARD Lecture Series No. 53, AGARD-LS-53, May 1972.

Technology Reviews

Powered Lift Technology

Powered lift refers to a concept of utilizing secondary airflows, typically supplied by means of an aircraft's propulsion system, to increase lift (and thus $C_{L,max}$) through an increase in wing circulation above that which is theoretically possible for unpowered wings. Numerous concepts have been explored over the past sixty years to accomplish this goal and several experimental aircraft have been built and flown for experimental testing (figure 1). However, to date, only one production fixed-wing aircraft, the McDonnell Douglas C-17 Globemaster, incorporates powered lift into its design (this ignores direct-lift thrust designs intended for vertical takeoff, as this topic is considered separately for purposes of this report). The performance, environmental, and safety benefits that may be derived through the use of powered lift (short takeoff and landing, reduced terminal area noise footprints, increased payload and range capability, and decreased landing speeds) necessitate an effort to understand the other factors arising in the decision to either include these concepts in future aircraft designs or not.

Three powered lift concepts are covered herein: a circulation control wing, blown flaps, and an augmentor/Jet wing. Most other concepts are slight deviations of these three with the exception of direct-lift thrust which is reserved for discussion as thrust vectoring technology. The concepts are discussed separately due to their unique technical characteristics, historical background, benefits and penalties, and configuration integration issues.

Reference.

1. Nielson, J. N.; and Biggers, J. C.: "Recent Progress in Circulation Control Aerodynamics", AIAA 87-0001, January 1987.

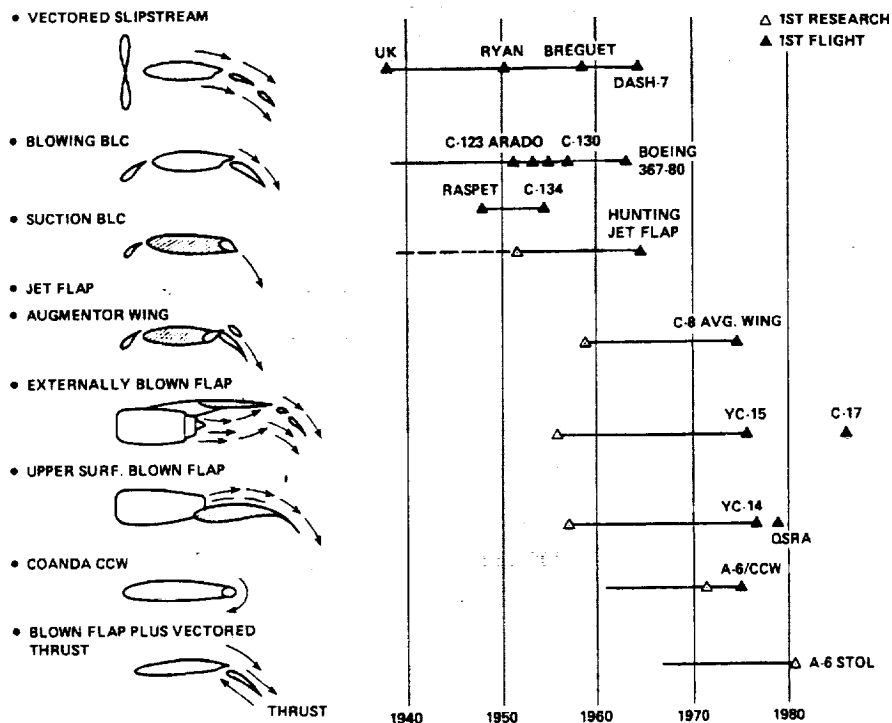


Figure 1. Powered Lift Chronology, from ref. 1

Circulation Control Wing

Technical Description. Circulation control refers to an aerodynamic configuration that incorporates an airfoil with a rounded trailing edge, an internal duct, and a slot on the upper surface near the trailing edge.

On a typical airfoil, the flow from the upper surface cannot turn around the sharp trailing edge without the velocity becoming infinite and, since this is impossible, the flow instead separates from the trailing edge. For a given airfoil angle of attack, separation at the trailing edge occurs for a particular value of the circulation and, hence, for a particular lift coefficient. A circulation control airfoil [ref. 1], on the other hand, has a rounded trailing edge, as shown in figure 1. Without blowing, a circulation control airfoil will have a separation point S1 on the upper surface. With blowing, the separation point S1 can move around the trailing edge onto the bottom surface. A slot is provided near the trailing edge such that the flow from the slot is tangent to the airfoil surface. The slot flow is at a higher speed than that of the local outer-flow and thus energizes the mixing boundary. This action permits the upper flow to remain attached until it reaches the separation point S1. From inviscid theory, the separation point S2 for the boundary layer on the lower surface coincides with S1; however, for a viscous fluid a "dead air" region can exist, with S1 and S2 at its extremities. The important principle to note is that there is a strong interaction between the outer inviscid flow and the jet flow, and that interaction determines airfoil circulation which thus determines its lift.

The lift of a circulation control airfoil is a direct function of turbulent mixing between the upper surface boundary layer and the slot jet. This turbulence mechanism is one of the major controlling factors in the process, and a good model of this mechanism is required for the rational prediction of flow about circulation control airfoils. Much effort has been focused on understanding this mechanism and in designing optimum circulation control wings (CCW). In 1986, a Circulation Control Workshop [refs. 2 and 3] was held at NASA Ames to establish the status of CCW for commercial and military applications and to identify research goals that are essential to its implementation for future fixed- and rotary-wing aircraft. The workshop was well attended by representatives from government agencies, industry and academia. The workshop resulted in a compilation of fundamental CCW research needs as well as specific research needs for CCW technologies for the X-wing, fixed-wing, NOTAR and tiltrotor applications. Since then numerous numerical [refs. 4 to 8] and experimental [refs. 9 to 14] studies have been conducted and knowledge of the CCW mechanisms have been greatly enhanced. The design of CCW wings, with optimum slot placement and size, airfoil shape, and performance is now possible [ref. 8].

Recently (1996) Dr. B. McCormick (Boeing Professor Emeritus) made a presentation titled, "Synergistic Effects of Propulsion for Aircraft" at LaRC [ref. 15]. In his talk Dr. McCormick presented a brief summary of high lift systems (mainly pertaining to V/STOL applications), some of which included circulation control concepts and their integration into the design of an aircraft. His concluding remarks included a rather strong statement: there are reams of test results in the literature on high lift systems and that further generic studies of high lift systems are not needed. What is needed, however, is application studies leading to design and construction of large scale models and an assessment of the net effect of integrating high lift systems with propulsion systems.

The basic concept of circulation control (CC) was developed at the David Taylor Naval Ship Research & Development Center (DTNSRDC) and has continued to be developed since the late 1960s. Many of these early developments are documented in references 16 and 17. The unique qualities of this concept are very attractive for many applications in the fields of aerodynamics and hydrodynamics.

To evaluate high lift potential, a Navy A-6/CCW demonstrator aircraft program was initiated in 1968 by DTNSRDC [ref. 18]. The aircraft configuration showing the CCW airframe changes is shown in figure 2. The principal aircraft modification included the incorporation of a circular trailing edge, attached to the existing flap, which forms both the Coanda surface, as well as bleed ducting. Existing

flow fences were removed and outboard flow fences added. The leading edge radius was increased and a fixed Krueger leading edge flap was added. A CCW air system powered by bleed air from the two engines was added. The bleed flow was controlled by throttle valves operated by the pilot.

The flight test of the A-6 confirmed previous wind tunnel predictions that the CCW could double the aircraft lifting capabilities while utilizing bleed air from the engines. A summary of the A-6/CCW aircraft performance as compared to the conventional A-6 is presented in figure 3. Following this test an advanced high lift system was developed that combined CCW and upper surface blown (USB) flaps to produce lift for STOL operations by Navy aircraft [refs. 19 and 20]. This combined system (USB/CCW) was found to be a very effective, yet simple method to control wing lift augmentation and vertical/horizontal force components. The original airfoil was modified at the trailing edge in order to have minimal impact on cruise efficiency. Several other modifications are documented in reference 21. The experimental results confirm thrust turning through angles up to 165 degrees and associated benefits as a STOL and thrust reverser system. Significant improvements in performance as compared to CTOL were found, since the maximum trimmed lift coefficient increased on the order of 200 percent. High-lift, vertical thrust, and thrust reversing were shown to be generated directly from the cruise configuration instantaneously and without external moving parts. Control of the thrust on takeoff and landing is directly controlled by the pilot (via bleed air) which is highly desirable for low speed lateral control. When compared to other high lift systems involving flaps and actuators, the USB/CCW system has significantly less moving parts. This contributes to increased reliability, maintainability, aircraft lifespan, and affordability (to first order; cost is proportional to weight and part count)..

The NASA Quiet Short-haul Research Aircraft (QSRA) is a high performance STOL powered lift research aircraft for which extensive low-speed wind-tunnel, flight simulation, and flight research testing has been conducted. In 1981 and 1983 the QSRA was reconfigured with a USB/CCW system and ground tested for the Navy to verify deflected engine thrust [refs. 22 and 23]. Circulation control capabilities were added and combined with the existing USB capability and are shown in figure 4; results of a study conducted on this configuration are documented in reference 24. A conclusion of the study was that flight verification is required to assess overall performance and control characteristics with fully integrated airframe, propulsion, and control system.

A program applying CCW to a Boeing 737 subsonic transport aircraft was planned and initiated in 1993 [refs. 19, 25, and 26]. The goal was to determine the feasibility and potential of pneumatic circulation control technology to increase high-lift performance while reducing system complexity and aircraft noise in the terminal area. (Terminal area noise is dominated by airframe noise, i.e., landing gear, flaps, non-streamlined protrusions). The study was four-phased and included experimental development and evaluation of advanced CCW high-lift configurations, development of pneumatic leading edge devices, computation evaluation of CCW airfoil designs, and evaluation of terminal-area performance employing CCW.

Figure 5 shows the high-lift and control surfaces for a conventional B737 and the B737/CCW aircraft. In its production version, the B737 employs a triple-slotted mechanical flap with leading edge slat. This sketch shows both this arrangement and the modified B737/CCW configuration. In the absence of actual full-scale flight test data for this aircraft, 1/8-scale wind tunnel results were used. The effect of including CCW was then computed. A comparison of lift coefficient (c_l) vs. angle of attack (α) for the conventional and CCW configuration is presented in figure 6, along with a drag polar. The study verified previous results showing the benefits of CCW.

McDonnell Douglas Helicopter Company (MDHC) has actually employed a circulation control device on a production helicopter. The anti-torque system of a helicopter has a major impact on the weight, performance, agility, reliability, flight and ground crew safety, and vehicle survivability. MDHC has been working on the No-Tail Rotor (NOTAR) concept for the past 20 years. This anti-torque system is in production and exists on current MD 500 series and Explorer vehicles. MDHC used

a structured approach to the development of this system. First, the performance of the individual NOTAR system components was measured and evaluated by experiment. Then, integrated system performance was investigated in ground testing, powered model rotor wind tunnel testing, and flight testing of 3 different aircraft: OH-6 Demonstrator, MD 520N/530N and MD 900 [refs. 9 and 10].

Currently, commercial utilization of circulation control on production aircraft is limited to rotorcraft. The McDonnell Douglas 500 series and the Explorer employ circulation control as an anti-torque device replacing the tail rotor. This application has also reduced the overall noise levels of the rotorcraft. For fixed wing the utilization is limited to experimental aircraft programs, such as the Navy/Grumman A-6 and the NASA QSRA, discussed above.

Current and/or Past Utilization. No current nor past production (unclassified) aircraft utilize circulation control wing for powered lift. Experimental aircraft programs have utilized the concepts with results discussed in the previous section.

Technological Benefits and Penalties. The primary benefit of circulation control is currently focused on providing high-lift on the order of C_L of 8 at zero angle of attack [ref. 26]. This magnitude of performance would greatly reduce takeoff and landing speeds, reduce runway lengths, and increase safety of flight in terminal areas. The resulting steep climbout and approach flight paths due to the STOL capability would also reduce the noise exposure to surrounding communities, thus increasing airport capacity. In addition, greatly increased liftoff gross weight and landing weight provided by the smaller wing area would allow transport wing designs that are more optimized for cruise and fuel efficiency. Compared to other high-lift wing/flap systems, the pneumatic CCW configurations reduce complexity and offer the opportunity to combine high-lift, roll control, and direct-lift-control surfaces into a single multipurpose pneumatic wing/control surface. Many of these identified benefits are concluded from component studies and/or studies where the effects on the total system were not fully investigated. In addition, the benefits do not fully account for the economics of design change costs which would be incurred if implemented on a production type aircraft.

Benefits of a circulation control wing are:

1. potential increase in $C_{L,max}$ by a factor of 4
2. reduction in part count which directly reduces overall cost
3. improved maneuverability and control
4. performance is primarily inviscid, thus reduces Reynolds number sensitivity
5. increased runway productivity by altering wake vortex and allowing several aircraft on same runway

Penalties and concerns for circulation control airfoils/wings are:

1. potential for increased base drag in cruise
2. decrease in thrust (estimated 5%) due to bleed flow requirement from engine compressor
3. asymmetric failure
4. system reliability
5. increased complexity and potential weight increase
6. cost/benefits analysis needed
7. true benefits unevaluated thus far.

Configuration Integration. There are several factors that need to be considered in designing a circulation control STOL aircraft, including:

1. Characteristics of the circulation control airfoil aerodynamics.
2. The relationship between the engine thrust lost and the bleed air requirement.

3. The lift loss associated with trimming unusually large pitching moments from circulation control aerodynamics.
4. Why is the locally obtainable lift coefficient about 6? What are the factors and design parameters that limit this?
5. CCWs may have abrupt wing-stall characteristics.
6. Rounded trailing edges, typical for CCW, must be retracted or modified for good cruise efficiency. (Note: the amount of "rounding" of the trailing edge can be very small to gain advantage, ref. 13)

References.

1. Nielson, J. N.; and Biggers, J. C.: "Recent Progress in Circulation Control Aerodynamics," AIAA 87-0001, January 1987.
2. Riddle, D. W.; and Eppel, J. C.: "A Potential Flight Evaluation of an Upper-Surface-Blowing/Circulation-Control-Wing Concept," Proceedings of the Circulation-Control Workshop 1986, NASA Ames Research Center, Moffett Field, CA, NASA CP 2432, February 19-21, 1986.
3. Nielson, J. N.: Proceedings of the Circulation-Control Workshop 1986, NASA Ames Research Center, Moffett Field, CA, NASA CP 2432, February 19-21, 1986.
4. Williams, S. L.; and Franke, M. E.: "Navier-Stokes methods to predict circulation control airfoil performance," *J. Aircraft*, Vol. 29, Mar.-Apr. 1992, p. 243-249.
5. Witherspoon, L. S.: "The Numerical Simulation of Circulation Controlled Airfoil Flowfields," Ph.D. Thesis, Stanford University, CA., 1993.
6. Himeno, R.; Kuwahara K.; and Kawamura, T.: "Computational Study of Circulation Control with Suction," AIAA 85-0042, January 1985.
7. Englar, R. J.; Smith, M. J.; Kelley, S. M.; and Rover III, R. C.: "Development of Circulation control Technology for Application to Advanced Subsonic Transport Aircraft," AIAA 93-0644, January 1993.
8. Wood, N. J.: "A New Class of Circulation Control Airfoils," AIAA 87-0003, January 1987.
9. Spaid, F. W.; and Keener, E. R.: "Boundary-Layer and Wake Measurements on a Swept, Circulation-Control Wing," *J. Aircraft*, Vol. 28, No.11, November 1991.
10. Dawson, S.; and Thompson, T.: "Recent NOTAR Anti-Torque System Research and Testing at MDHC," 49th AHS Annual Forum, Saint Louis, MO, May 19-21, 1993.
11. Kozachuk, A. D.: "Experimental Studies of Air Flow in the Channel of a Circulation-Control Rotor Blade," Problems in the design of helicopter rotors (A93-32173 12-05), Izdatel'stvo Moskovskogo Aviatsionnogo Instituta, Russia.
12. Franke, M. E.; Pelletier, M. E.; and Trainor, J. W.: "Circulation Control Wing Model Study," AIAA 93-0094, January 1993.
13. Englar, R. J.; Nichols, J. H., Jr.; Harris, M. J.; and Huson, G.: "Experimental Development of an Advanced Circulation Control Wing System for Navy STOL Aircraft," AIAA 81-0151, January 1981.
14. McLachlan, B. G.: "A Study of a Circulation Control Airfoil with Leading/Trailing Edge Blowing," AIAA 87-0157, January 1987.
15. McCormick, B. W.: "Synergistic Effects of Propulsion for Aircraft," Presentation made at NASA LaRC, Sept. 12, 1996.
16. Englar, R. J.; Stone, M. B.; and Hall, M.: "Circulation Control - An Updated Bibliography of DTNRDC Research and Selected Outside References," DTNSRDC Report 77-076, September 1977.
17. Englar, R. J.; and Applegate, C. A.: "Circulation Control - A Bibliography of DTNSDRDC Research and Selected Outside References," DTNSRDC Report 84-052, October 1984.
18. Pugliese, A. J.; and Englar, R. J.: "Flight Testing the circulation Control Wing," AIAA 79-1791, August 1979.
19. Englar, R. J.: "Development of the A-6/Circulation Control Wing Flight Demonstrator Configuration," DTNSRDC Report ASED-79/01, January 1979.
20. Nichols, J. H.; and Englar, R. J.: "Advanced Circulation Control Wing System for Navy STOL Aircraft," AIAA 93-0094, August 1980.

21. Nichols, J. H.; and Harris, M. J.: "Fixed Wing CCW Aerodynamics With and Without Supplementary Thrust Deflection," N88-17607, presentation only, no paper.
22. Eppel, J. C.; Shovlin, M. D.; Janes, D. N.; Englar, R. J.; and Nichols, J. H.: "Static Investigation of the Circulation-Control-Wing/Upper-Surface-Blowing Concept Applied to the Quiet Short-Haul Research Aircraft," NASA TM 84-232, 1982.
23. Englar, R. J.; Nichols, J. H.; Harris, M. J.; Eppel, J. C.; and Shovlin, M. D.: "Circulation Control Technology Applied to Propulsive High Lift Systems," SAE Paper 84-1497, October 1984.
24. Englar, R. J.; Hemmerly, R. A.; Moore, W. H.; Seredinsky, V.; Valckenaere, W. G.; and Jackson, J. A.: "Design of the Circulation Control Wing STOL Demonstrator Aircraft," AIAA 79-1842, August 1987.
25. Englar, R. J.; Smith, M. J.; Kelley, S. M.; and Rover III, R. C.: "Application of Circulation Control to Advanced Subsonic Transport Aircraft, Part II: Transport Application," *J. Aircraft*, Vol. 31, No. 5, September-October 1994.
26. Englar, R. J.; Smith, M. J.; Kelley, S. M.; and Rover III, R. C.: "Application of Circulation Control to Advanced Subsonic Transport Aircraft, Part I: Airfoil Development," AIAA 93-0644, January 1993.

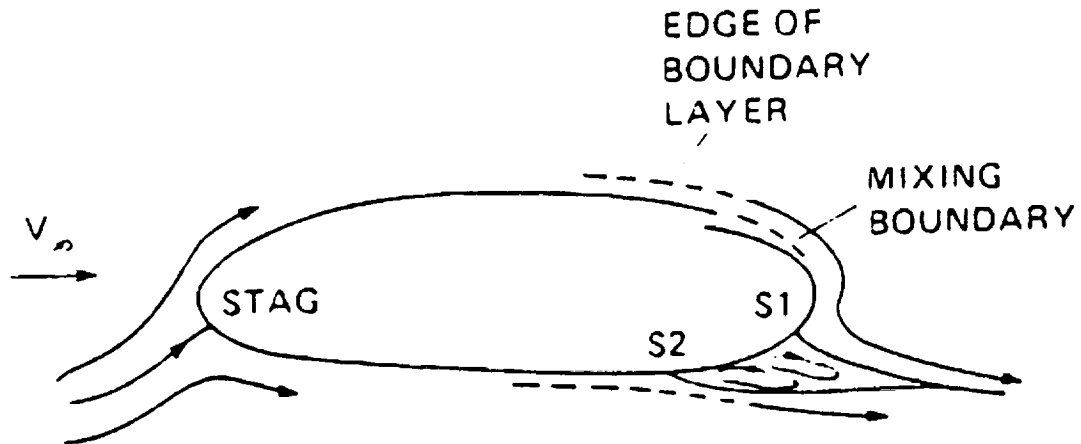


Figure 1. Flow circulation about a circulation control aircraft, from ref. 1.

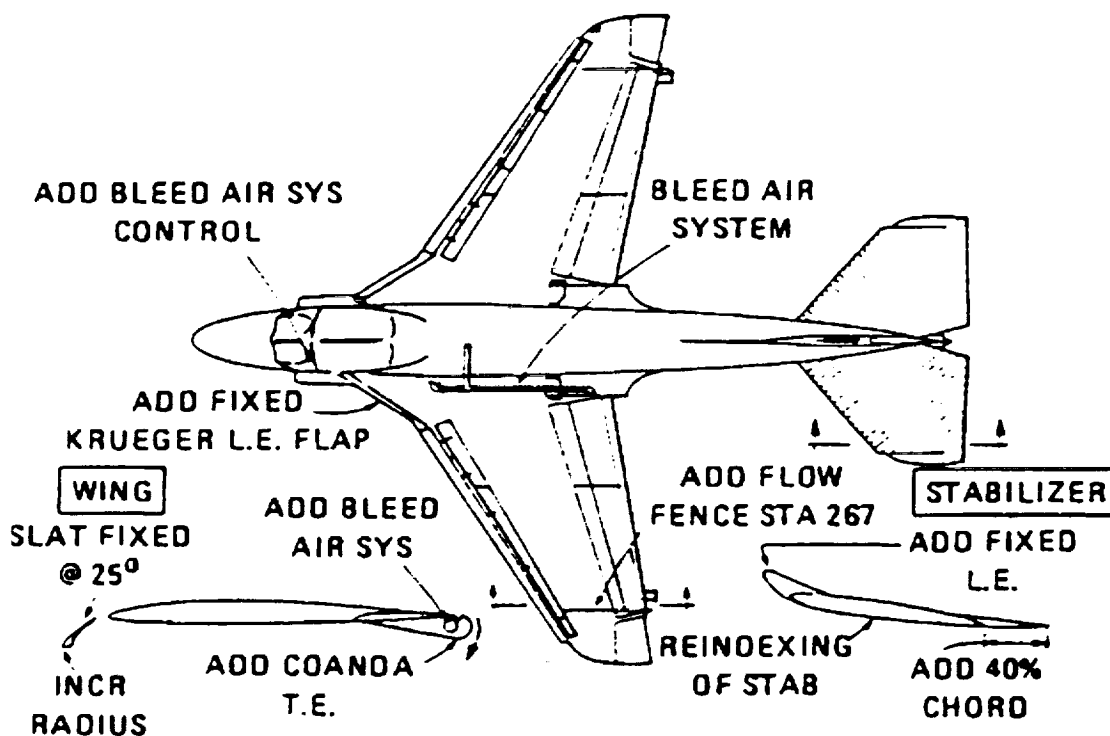


Figure 2. CCW airframe modifications, from ref. 19.

	A 6 (30 FLAPS) (REF)	A 6/CCW
85% INCREASE IN C_{LMAX}	2.1	3.9 ($C_{\mu} = 0.30$)
35% REDUCTION IN POWER-ON APPROACH SPEED	118 knots ($C_L = 1.49$)	76 knots ($0.75 P_{MAX}$, $C_{\mu} = 0.14$, $C_L = 2.78$)
65% REDUCTION IN LANDING GROUND ROLL	2450 ft	900 ft
30% REDUCTION IN LIFT OFF SPEED	120 knots ($C_L = 1.41$)	82 knots ($0.6 P_{MAX}$, $C_{\mu} = 0.04$, $C_L = 2.16$)
60% REDUCTION IN TAKEOFF GROUND ROLL	1450 ft	600 ft
75% INCREASE IN PAYLOAD/FUEL AT TYPICAL OPERATING WEIGHT (EW = 28,000 lb)	45,000 lb	58,000 lb

BASED ON FLIGHT DEMONSTRATION RESULTS
TOGW = 35,700 lb, LGW = 33,000 lb
CORRECTED TO SEA LEVEL, STANDARD DAY

Figure 3. A-6/CCW STOL performance, from ref. 15.

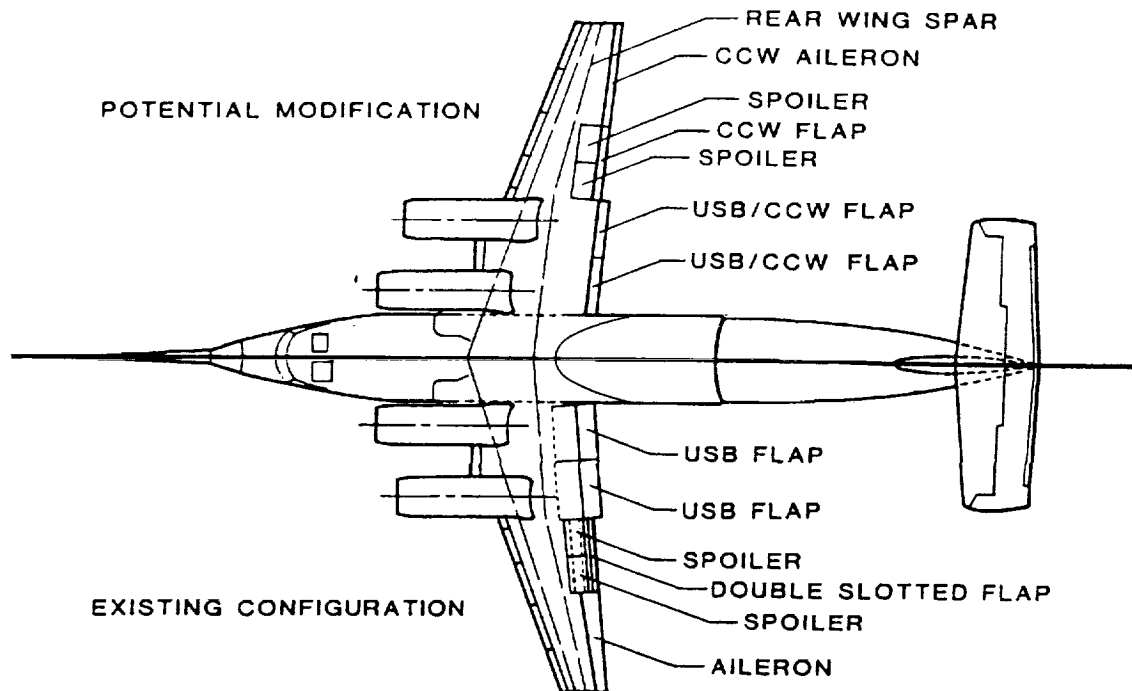


Figure 4. Comparison of existing QSRA wing to a USB/CCW modification, from ref. 14.

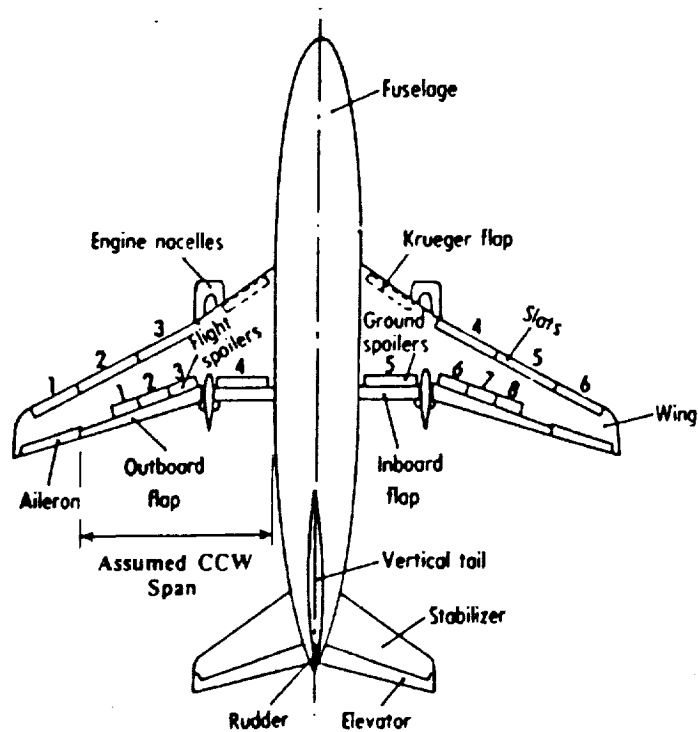


Figure 5. High-lift and control surfaces for conventional B737 and B737/CCW aircraft, from ref. 26.

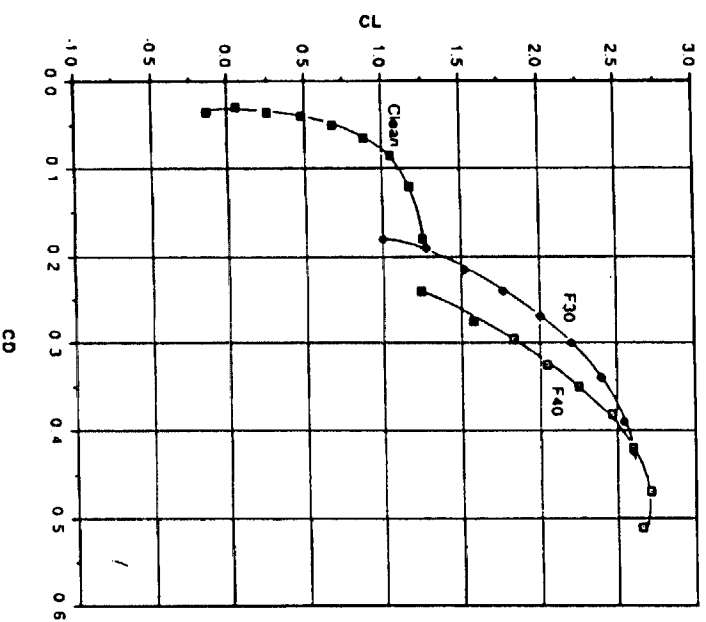
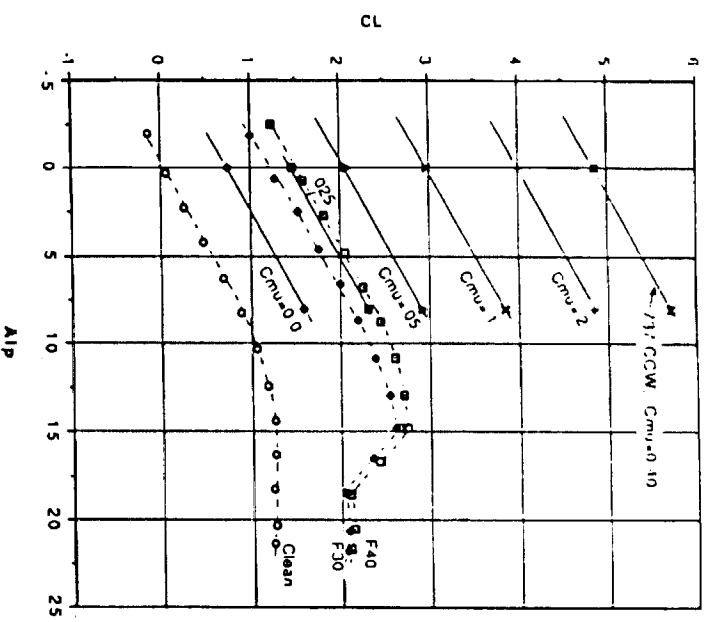


Figure 6. 1/8-scale wind tunnel lift and drag data for B737 (clean) aircraft compared with predicted B737/CCW (F30, F40) data, from ref. 26.

Blown Flaps

Technical Description. Blown flaps are a subset of powered lift technology where the vehicle lift is augmented by blowing over, under, or through wing trailing-edge flaps using either engine bleed air or engine exhaust flows. These systems achieve increased lift by increasing wing circulation and, to some extent, by deflecting thrust downward. These systems can significantly increase the maximum lift coefficient ($C_{L,max}$) of the aircraft and thus, provide STOL capability. Figure 1 shows the range of $C_{L,max}$ values possible by various techniques as a function of wing aspect ratio. Plain wings are limited to values well below 1.5. Mechanical flaps increase $C_{L,max}$ to around 2.0. Blowing boundary layer control (BLC) is limited to values around 4.0. For $C_{L,max}$ values above 4.0, forced circulation is required; further increases require the addition of direct thrust. Blown flap systems can be grouped into two general categories, internal flow systems and external flow systems. The internal flow systems utilize internal ducts to eject air over the flap(s), and the external flow systems exploit favorable placement of the engine and flap(s). The flap systems described herein are categorized in the manner of references 1 and 2.

There are at least four varieties of internal flow blown flap systems. They are blowing boundary layer control, the circulation control wing (discussed earlier), the jet flap, and the augmentor wing. These systems are shown in figure 2. In all four systems bleed air is ducted to and ejected over the flap upper surface.

Blowing boundary layer control (BLC) was first explored in the 1920s; systematic studies were performed in the 1940s and 1950s. This system makes use of engine bleed air to energize the boundary layer on the upper surface of the wing and delay flow separation. This allows a much higher maximum lift coefficient to be achieved. The Boeing 367-80 (707) prototype airplane demonstrated a BLC high lift system [ref. 3]. During flight testing, lift coefficients of at least 3.3 at a speed of 73 knots were obtained. For comparison, the maximum lift coefficient for a Boeing 707 is approximately 1.7 at a speed of 102 knots.

The internal flow jet flap is unique in that a large percentage of the engine exhaust is deflected through trailing-edge slots and over the flap. This system was initially proposed and tested in 1932, and it was demonstrated on the Hunting jet flap research airplane in the 1960s. For this configuration, lift coefficients greater than 6.0 were measured in the Langley 7x10-Foot Low Speed Wind Tunnel, and coefficients as high as 9.0 were measured during flight tests of the full scale vehicle [ref. 5]. The augmentor wing is a variation of the jet flap. It has a shroud assembly over the flap to create an ejector system which augments the thrust of the nozzle by entraining additional air. A DeHavilland C-8A was modified to include the augmentor wing design [ref. 6]. For this configuration lift coefficients of up to 5.5 were obtained.

There are two varieties of external flow blown flaps systems shown in figure 3. They are the externally blown flap (EBF) and the upper surface blown (USB) flap. Both approaches utilize relatively conventional flap designs. The EBF approach uses conventional pod-mounted engines which blow exhaust on the lower surface of the flaps [ref. 7]. The USB design has engines mounted on the upper surface of the wings and blow exhaust over the upper surface of the wing and flaps [ref. 8]. These two systems have similar aerodynamic characteristics, and demonstrated operational performance. During the 1970s the EBF design was first demonstrated on the YC-15 research aircraft and the USB system was first demonstrated on the YC-14 research aircraft. The USB approach has somewhat better noise characteristics than the EBF approach as the wings tend to shield engine exhaust noise from the ground [ref. 9].

The general performance characteristics of the internal and external flow systems are compared with deflected thrust approaches in figure 4. This plot provides an indication of the amount of thrust used to produce a direct lifting force versus the amount used to increase wing circulation. Deflected thrust is another powered lift concept in which the engines are used directly to produce a lifting force

and wing circulation is not augmented. Internal flow systems are the most aerodynamically efficient because they provide the greatest increase in wing circulation for a given level of thrust, followed by external flow systems. While this implies that internal flow systems are superior, this result is tempered by the fact that engines appropriate for use with externally blown flaps have a relatively low fan pressure ratio and provide more static thrust than engines for internally blown flaps designed for the same cruise thrust. This difference in engine fan pressure ratio tends to balance out the difference in flap efficiency so that overall performance is not greatly different for the two flap systems. Clearly the choice between the various systems needs to be considered in the context of the entire aircraft design.

A unique implementation of the USB concept is the channel wing [refs. 10, 11, 12, and 13]. The channel wing, often referred to as the Custer Channel wing after its promoter Willard Custer, integrates the propeller flow with the wing aerodynamics by using the wing as a "shroud" in front of and below the propeller (Figure 5). The propeller draws its flowstream over the wing, inducing high upper-surface flow velocities at low airspeeds. This increases the circulation of the wing and provides a powered-lift capability similar to that of jet-powered USB systems.

It is possible for aircraft to employ more than one of these concepts to achieve greater STOL capability. One such aircraft is the NASA Quiet Short-haul Research Aircraft (QSRA), first mentioned in the Circulation Control discussion. This aircraft was originally configured with inboard USB flaps and blown BLC ailerons which can be drooped during flight to effectively provide a nearly full-span blown flap system. In addition, the wing had a leading-edge flap with blowing BLC [refs. 14 and 15]. This aircraft was able to obtain maximum lift coefficients as high as 10.

One final point needs to be made regarding high lift systems. With an increase in the operational lift coefficient comes a reduction in the vehicle airspeed and a reduction in the effectiveness of conventional control surfaces. Consequently, jet reaction control or blowing BLC for roll, yaw, and pitch control may be required. In addition, increased reliance on powered lift systems also increases the difficulty of achieving a design that can tolerate engine failures, which increases system complexity.

Current and/or Past Utilization. The McDonnell Douglas C-17 is the only transport currently in production employing powered lift technology. The design employs an externally blown, double-slotted, trailing-edge flap. Lift augmentation is achieved by deflecting the flap into the exhaust from engines mounted under the wing. An unusual aspect of the C-17 is the fact that it is the first powered-lift airplane to demonstrate the value of increased lift capability from powered-lift for increased payload rather than for emphasis on increased takeoff and landing performance.

Technological Benefits and Penalties. STOL aircraft have enhanced in-flight capabilities that include steep-gradient and curved-flight departures and approaches, high rates of climb, steep final descents, high maneuverability, rapid response for aborted landing, and low landing-approach speeds. These characteristics yield aircraft that require less airspace in the near-terminal area, require less ground space at the terminal, operate with less noise, and have improved crashworthiness and survivability because of their low speed capability at near-level fuselage attitudes. Thus, the use of existing airport infrastructure could be enhanced by utilizing vacant airspace, operating from separate short runways, minimizing time on the runway, and operating from presently underutilized small terminals. Also, the cost of new terminals could be minimized, and new modes of operation such as high-speed transportation directly to and from corporate headquarters and factories could be stimulated. Application to military missions include supply at more desirable, forward sites, operation on damaged runways, and enhanced operations from naval vessels.

All of the technologies discussed in the preceding section have the benefit of increasing the maximum lift coefficient of the aircraft. This effect allows all of these technologies to effectively reduce noise by allowing the aircraft to climb faster and achieve a higher altitude prior to overflying populated

areas. This is in spite of the fact that source noise of these concepts generally increases due to the interaction of the propulsion system with the wing and flaps. The equivalent noise footprint of a STOL vehicle may be an order of magnitude less than that of comparable conventional aircraft [ref. 16]. Thus, resistance to new terminal projects can be minimized due to greater public acceptance.

Two penalties for employing these lift augmentation technologies are increased integration difficulties and mechanical complexity. The internal flow systems are the most efficient in terms of required thrust to weight ratio, but they suffer the largest penalties. They are complex, require more maintenance, have a higher initial cost, have engine performance penalties, and have structural and weight problems as compared with their external flow counterparts. The external flow systems do not experience these difficulties, but have lower aerodynamic efficiency and have higher required thrust-to-weight ratios.

Configuration Integration. Five primary issues for integrating blown flaps into an aircraft design are:

1. Engine placement relative to wing (EBF, USB, internal flow)
2. Engine air ducting and routing (internal flow only)
3. Structural layout of the wing box, movable flaps, and ducts
4. Flight control effectors for low-speed or vertical flight
5. Stealth

Engine placement relative to the wing is extremely important to EBF concepts due to the close interaction of emitted thrust flows with the wing and flap aerodynamics and optimization for both STOL operations and cruise. USB concepts require careful attention to wing/engine integration to ensure acceptable cruise performance of the wing aerodynamics. Internal flow designs require the consideration of engine placement for the integration of ducting from the engine exhaust path to the wing locations desired for blowing. The ducting itself encounters trade-offs between a desire for short duct lengths for minimum weight and a desire for large radii of curvature for maximum internal flow efficiency. Both the engines and the ducting must consider their volume impacts on the wing box structural design and possible load path implications. As mentioned, at very low STOL speeds, traditional control surfaces lose effectiveness, requiring unconventional configurations or control devices. Stealth issues are important in determining the flap arrangement and engine exhaust locations for military vehicles. Additionally, the acoustic qualities of STOL operations produce inherent, non-traditional stealth applications for covert insertions.

References.

1. Johnson, J. L.: "Review of Powered Lift Technology, Aerodynamic Considerations," Eagle Engineering, Inc., Hampton Division. October 1991.
2. Deckert, W. H.; and Franklin, J. A.: "Powered -Lift Aircraft Technology," NASA SP-501, December 1989.
3. Grazter, L. B.; and ODonnell, T. J.: "Development of a BLC High-Lift System for High-Speed Airplanes," *J. Aircraft*, November-December 1965.
4. Englar, Robert J.: "Development of the A-6/Circulation Control Wing Flight Demonstrator Configuration," DTN SRDL/ASED-7901, January 1979.
5. Harris, K. D.: "The Hunting H.1326 Jet-Flap Research Aircraft. Assessment of Lift Augmentation Devices," AGARD, LS-43-71, 1971.
6. Quitley, Hervy, C.; and Innis Robert C.: "A Flight Investigation of the STOL Characteristics of an Augmented Jet Flap STOL Research Aircraft," NASA TM X-62334, 1974.
7. Campbell, John P.; and Johnson, Joseph L., Jr.: "Wind-Tunnel Investigation an External Flow Jet-Augmented Slotted Flap Suitable for Application to Airplanes With Pod-Mounted Engines," NASA TN-3898, 1956.

8. Turner, T. R.; Davenport, E. E.; and Riebe, J. M.: "Low-Speed Investigation of Blowing From Nacelles Mounted Inboard and on the Upper Surface of an Aspect Ratio 7.0 35° Swept Wing With Fuselage and Various Tail Arrangements," NASA Memo 5-1-59L, 1959.
9. Maglieri, D. J.; and Hubbard H. H.: "Preliminary Measurements of the Noise Characteristics of Some Jet-Augmented-Flap Configurations," NASA Memo 12-4-58 L, 1959.
10. Young, D. W., "Test of Two Custer Channel Wings Having a Diameter of 37.2 Inches and Lengths of 43 and 17.5 Inches", Army Air Forces Technical Report 5568, April 1947.
11. Pasamanick, J.; "Langley Full-Scale Tunnel Tests of the Custer Channel Wing Airplane", NACA Research Memorandum L53A09, April 1953.
12. Anderton, D. A.; "Vertical Lift is Claimed for Channel Wing", Aviation Week, December 17, 1951.
13. Blick, E. F. and Homer, V.; "Power-On Channel Wing Aerodynamics", Journal of Aircraft, Vol. 8, No. 4, April 1971, pp. 234-238.
14. Eppel, J. C.; Shovlin, M. D.; Jaynes, D. J.; Englar R. J.; and Nichols, J. H., Jr.: "Static Investigation of the Circulation-Control-Wing/Upper Surface-Blowing Concept Applied to the Quiet Short-Haul Research Aircraft," NASA TM-84232, 1982.
15. Stephens, V. C.; Riddle, D. W.; Martin, J. L.; and Innis, R. C.: "Powered-Lift STOL Aircraft Shipboard Operations - A Comparison of Simulation, Land-Based and Sea Trial Results for the QSRA," AIAA 81-2480, November 1981.
16. Brown, D. G.: "The Case for V/STOL Aircraft in Short-Haul Transportation," SAE National Air Transportation Meeting, Paper No. 700333, April 1970.

Bibliography.

- Langford, John S., III: "The NASA Experience in Aeronautical R&D: Three Case Studies With Analysis," IDA Report R 319, March 1989.
- Englar, R. J.; Niebur, C. S.; and Gregor, S. D.: "Pneumatic Lift and Control Surface Technology Applied to High Speed Civil Transport Configurations," AIAA 97-0036, January 1997.
- Johnson, W. G.: "Aerodynamic Characteristics of a Powered, Externally Blown Flap STOL Transport Model With Two Engine Simulator Sizes," NASA TN D-8057, November 1975.
- Powered-Lift Aerodynamics and Acoustics. Conference held at Langley Research Center, Hampton, VA, NASA CP-406, May 24-26, 1976.
- Antinello, John S.: "Design and Engineering Features of Flap Blowing Installations," *Boundary Layer and Flow Control*, Pergamon Press, 1961, pp. 462-515.
- Davidson, I. M.: "The Jet Flap," *J. Royal Aeronautical Society*, Vol. 60, January 1956.
- Malavard, L.; Poisson-Quinton, P.h.; and Joussenanodot, P.: "Theoretical and Experimental Investigation of Circulation Control," Princeton University Report No. 358, July 1956.
- Lockwood, Vernard E.; Turner, Thomas R.; and Riebe, John M.: "Wind Tunnel Investigation of Jet-Augmented Flaps on a Rectangular Wing to High Momentum Coefficients," NACA 3865, 1956.
- Cone, Clarence D., Jr.: "A Theoretical Investigation of Vortex-Sheet Deformation Behind A Highly Loaded Wing and Its Effect on Lift," NASA TN D-657, 1961.
- Nichols, J. H., Jr.; Englar, R. C.: "Advanced Circulation Control Wing System for Many STOL Aircraft," AIAA 80-1825, August 1980.

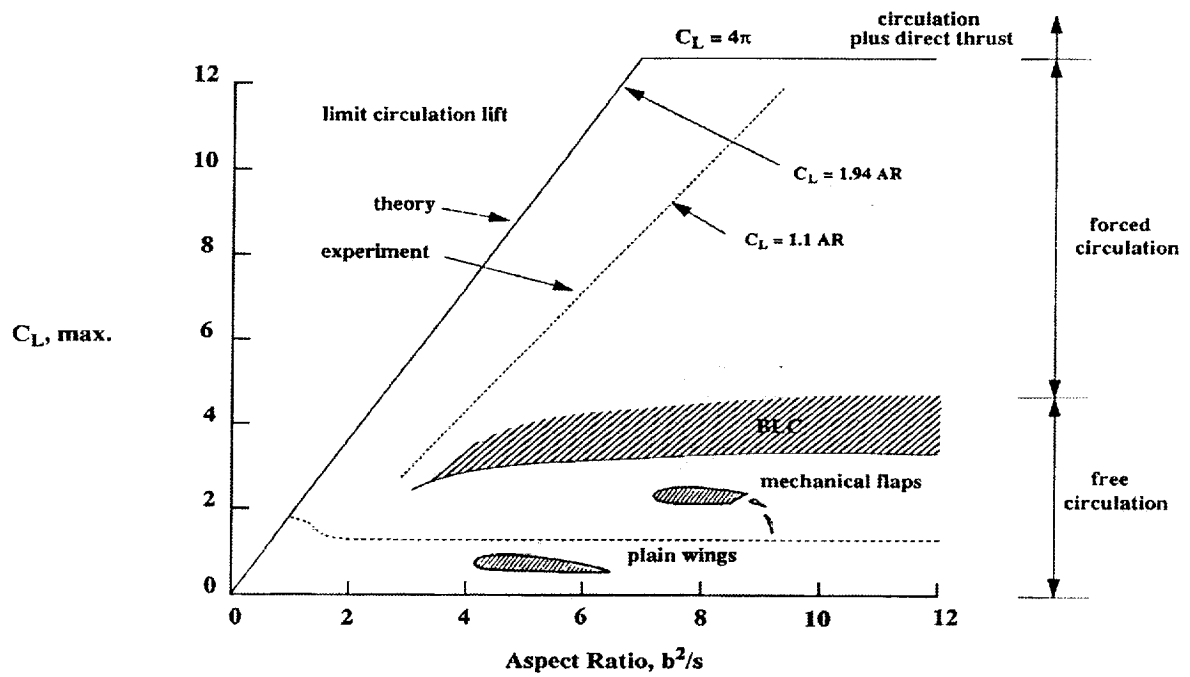
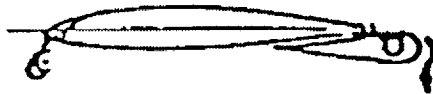


Figure 1. Maximum lift coefficient as a function of aspect ratio.

Blowing BLC



Circulation Control Wing



Jet Flap



Augmentor Wing



Figure 2. Internal flow, blown flap systems.

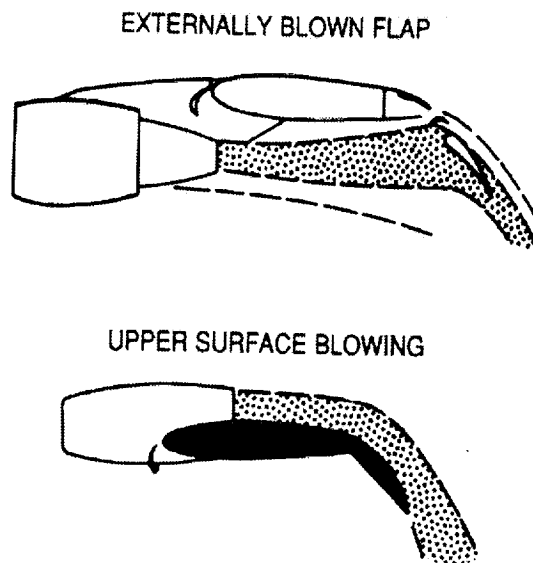


Figure 3. External flow, blown flap systems.

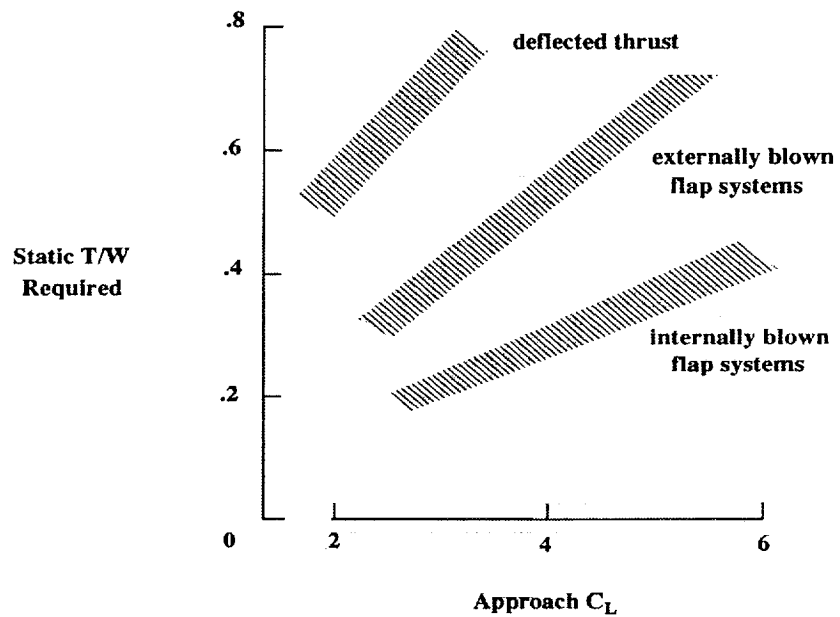


Figure 4. Comparison of thrust requirements of internally and externally blown flaps with deflected thrust approaches.



Figure 5. The Channel Wing

Augmentor/Jet Wing

Technical Description. The ejector/augmentor wing and Jetwing are two examples of powered lift technology. Other examples of powered lift include internally and externally blown flaps, upper surface blowing, thrust vectoring, and lift-fan or direct-lift engines. Envisioned as a means of achieving good V/STOL performance for military aircraft, these technology concepts have been investigated experimentally and computationally since the 1950's.

Powered lift technologies utilize propulsion bleed and/or exhaust flows to increase wing circulation. This is accomplished through various means: entrainment of external flows, super-velocity acceleration of flows, and direct vectoring of propulsive flows in the lift vector orientation. Cross-sectional wing schematics for various powered lift technologies are shown in figure 1.

There are two general approaches to the ejector/augmentor concept which will be referred to as the XFV-12A and E-7A concepts due to their usage within those experimental aircraft test programs. The XFV-12A concept for ejector/augmentor wings is a V/STOL application that typically consists of three trailing-edge flap elements arranged as shown in figure 2. The center flap element contains ejector augmentors which blow propulsive air in the lift direction. The jet created by these ejectors serves to entrain airflow over the surface of the other two flaps which act to form a diverging nozzle. In addition, the two lower flaps contain Coanda surfaces to further assist in flow entrainment. The concept results in a lift force greater than the propulsive force utilized, thus "augmenting" the power output by the engines. An internal layout drawing of the XFV-12A is shown in figure 3. Note that both the main wing and the canard are configured as ejector/augmentor wings and that the vehicle is a single engine, supersonic aircraft.

The E-7A ejector/augmentor concept is also a V/STOL application and consists of a channel through each wing, near the root, where a series of deflectable ejector vanes are arranged (figures 4 to 6). Fan air is diverted to these ejectors as well as through an aft centerline nozzle fixed in both a forward thrust and lift contributing axis. The ejector/augmentors serve to entrain flow from over the wing surface through the channel and thus create a thrust augmentation through supercirculation. The bottom portion of the wing channel is opened into a nozzle through a complex mechanism and closes to form a sealed, supersonically viable configuration.

The Jetwing concept, developed by the Bell-Bartoe Aircraft Company, is a STOL concept with two basic configurations. Figure 7 shows a concept utilizing a second wing, forming an ejector between it and the main wing. The leading edge section of the main wing contains a duct and plenum through which air is blown over the upper surface of the wing. This blown flow entrains additional flow through the ejector area. A Coanda surface on the trailing edge flap serves to create high flow turning angles and completes the high-lift concept. Figure 8 shows the other version of the concept without the ejector that utilizes only upper surface blowing and the Coanda flap. An internal layout of the engine and ducting of the Bell-Bartoe Experimental Jetwing Aircraft is shown in figure 9. Note that all of the airflow, including both the fan and core flows, are directed entirely to the wing.

Current and/or Past Utilization. No current nor past production (unclassified) aircraft utilize either the ejector/augmentor wing or Jetwing design concepts for powered lift. Experimental aircraft programs have utilized the concepts with results discussed in the previous section. V/STOL technology is generally viewed as most valuable in military applications where short field capabilities or carrier-based operations are required. Future civilian requirements in community noise restriction, air traffic congestion, airport layout design constraints, and the business transportation market may present the possibility of new markets for V/STOL technologies.

Technological Benefits and Penalties. Studies have demonstrated that the ejector/augmentor wing and Jetwing concepts have benefits in performance, noise, emissions, and safety. There may be addi-

tional benefits in life-cycle cost savings and air traffic throughput achieved through the usage of these concepts.

There appears to be little publicly available performance data on the ejector/augmentor wing, probably due to the classification on the Navy/Rockwell XFV-12A program. However, figure 10 shows the split between circulation lift and jet lift for the ejector/augmentor concept in the XFV-12A at various flight speeds without indicating the lift coefficient. Note that the lift generated by circulation is zero for no forward flight, indicating vertical takeoff, and that the ejector/augmentor lift goes to zero at 140 knots. Figure 11 shows the mechanical transition of the XFV-12A ejector/augmentor wing from hover to cruise.

The proponents of the XFV-12A concept wing demonstrated in laboratory tests that the augmentation ratio, defined as the ratio of the total thrust generated to the primary thrust injected at the ejector/augmentor, could exceed 2.0. If such performance was attainable in a flight article, the takeoff and climbing benefits would be capable of offsetting the additional weight of necessary flow diverters and ducting.

The General Dynamics E-7A incorporates a very different concept of ejector/augmentors but the physics of the thrust augmentation procedure are the same. The primary implementation distinction is that the E-7A utilizes a secondary nozzle for vectored engine core thrust while a portion of the fan-diverted flow exits through a 2-D afterburning nozzle (figure 5). Figure 12 depicts the thrust distribution for hovering, transitional, and forward flight. The concept was tested in static and free-flight wind-tunnel tests during the late 1980's and early 1990's and appeared to be feasible. There may possibly have been some issues with both design complexity and stealth configuration that prevented the Lockheed Martin JAST team from proposing the concept for use in what is now the Joint Strike Fighter (JSF) program.

The V/STOL performance capabilities afforded through powered lift generate possible overall aircraft weight savings through reductions in fuel burn during takeoff, climb, descent, and landing operations. This reduction in fuel burn is possible due to higher vertical climb/descent rates used to reach or descend from cruise altitude in a shorter time than otherwise possible. This fuel savings results in an overall smaller (and lighter) aircraft, possibly costing less to manufacture and certainly costing less to fuel, and producing reduced emissions through reduced fuel burn. Accelerated climbouts additionally hold the potential for increased airport operations due to a decrease in necessary aircraft spacing, a variety of climb and descent profiles available to pilots and controllers, and through achieving community noise footprints likely superior to conventional aircraft due to shorter dwell times, higher altitudes, and reduced jet velocities.

In addition to the V/STOL capabilities afforded by the ejector/augmentor wing, these concepts hold key advantages in noise and "hot footprint" which translate directly to human safety benefits when compared to other V/STOL fixed wing aircraft. Figure 13 depicts noise levels for various powered lift concepts with ejector/augmentor wings and the Jetwing (Upper Surface Blown or USB in that figure) shown as the minimal noise producing concepts. A V/STOL aircraft produces patterns of hot exhaust which have two major effects: 1) limiting the proximity and type of materials/objects which can be present in the landing and takeoff area and 2) causing "hot day" performance and engine damage through ingestion of exhaust flows. Due to the superior flow mixing and resultant cooling of exhaust flows in the ejector/augmentor wing and the Jetwing, neither of these issues is a serious performance limiter. Hot and blast jet exhaust zones are severely decreased for these aircraft, increasing the safe maintenance and operations area available to personnel conducting pre- and post-flight servicing.

In addition to V/STOL capabilities for takeoff and landing operations, the performance capabilities of these propulsion integration concepts hold the potential to increase the survivability of military aircraft due to superior maneuvering capabilities. The University of Tennessee Space Institute published a paper [ref. 1] including a conceptual design study indicating maneuvering performance enhancements

due to the Jetwing concept. Figures 14 and 15 show the reported benefits in turn rate and sustained normal load factors at sea level and combat altitude. The resulting configuration is shown in figure 16. Battle damage survivability can be poor depending on the exhaust arrangement of V/STOL aircraft. For example, Harriers tend to take heat seeking missiles amidship.

Three significant penalties inhibit the adoption of augmentor and Jetwing concepts: additional weight due to ducting and mechanical systems, constraints on design integration (see configuration integration) due to ducting and balance considerations, and the expense of system complexity. No data was publicly available on the details of system weight for any of the experimental vehicles and studies investigating the penalties associated with design of augmentor and Jetwing concepts must overcome the large uncertainties associated with systems weight and ducting losses. The associated life cycle cost -- especially in maintenance -- is a significant unknown with little applicable data existing either within the public domain or industry proprietary data.

Configuration Integration. Five primary issues for integrating either of these concepts into an aircraft design are:

1. Center of gravity location
2. Engine air ducting and routing
3. Structural layout of the wing box, movable flaps, and ducts
4. Flight control effectors for low-speed or vertical flight
5. Stealth

Center of gravity location is critical for thrust balance in a VTOL aircraft. It is the major factor in tail design for STOL aircraft. Engine air ducting allowances must be made in both the fuselage and wing for fuselage embedded engine aircraft. Significant turn radii are required for diverting the flow forward in these ducts while preventing separation. The ducts must fit within the thickness of the wing section making supersonic aircraft much more difficult to integrate while limiting wave drag. Finally, the ducts will take up volume normally used for fuel. The structural layout options greatly impact the weight of the wing due to positioning of primary structural members and carrying the structural loads from numerous, highly aerodynamically loaded flight controls and flaps. Flight control is a critical element of a V/STOL design due to limitations on the available effectiveness of primary flight controls. Many ejector/augmentor concepts for hovering and transitioning flight utilize pneumatic controls functioning off of the diverted propulsion flow. STOL flight controls concepts include both pneumatics and enlarged main control surfaces. The ability to include powered lift technologies in stealth designs is debatable. The required geometry and material treatment are difficult to achieve with concepts requiring large numbers of moving parts, internal chambers, and exposure to engine exhaust gases.

References.

1. Kimberlin, R. D.; and Sinha, A. K.: "STOL Attack Aircraft Design Based upon an Upper Surface Blowing Concept," AIAA 83-2535, 1983.
2. Andrews, H.; Murphy, R.; and Wilken, I.: "The North American Rockwell XfV-12A - Reflections and Some Lessons," AIAA 90-3240, 1990.
3. Whitley, D. C.; and Gilbertson, F. L.: "Recent Developments in Ejector Design for V/STOL Aircraft," SAE Paper 841498, January 1984.
4. Kimberlin, R. D.: "An Investigation of the Effects of a Thrust Augmenting Ejector on the Performance and Handling Qualities of an Upper Surface Blown Research Aircraft," Flight testing technology: A state-of-the-art review, Proceedings of the Thirteenth Annual Symposium, New York, NY, September 19-22, 1982 (A84-44451 21-01). Lancaster, CA, Society of Flight Test Engineers, 1982, p. 67-72.
5. Riley, D. R.; Shah, G. H.; and Kuhn, R. E.: "Low-Speed Wind-Tunnel Study of Reaction Control-Jet Effectiveness for Hover and Transition of a STOVL Fighter Concept," NASA TM 4147, December 1989.

Bibliography.

- Kimberlin, R. D.: "Performance Flight Test Evaluation of the Ball-Bartoe JW-1 Jetwing STOL Research Aircraft," Flight testing in the Eighties; Proceedings of the Eleventh Annual Symposium, Atlanta, GA, August 27-29, 1980. (A82-20751 08-05) Lancaster, CA, Society of Flight Test Engineers, 1980, p. 16-1 to 16-20.
- Kimberlin, R. D.; Solies, U. P.; and Sinha, A. K.: "A Flight Test Evaluation and Analytical Study of the Ball-Bartoe Jetwing Propulsive Lift Concept Without Ejector," University of Tennessee Space Institute Report UTSI-82/17, Oct. 1, 1982.
- Sinha, A. K.; Kimberlin, R. D.; and Wu, J. M.: "Equivalent Flap Theory: A New Look at the Aerodynamics of Jet-Flapped Aircraft," AIAA 84-0335, 1984.
- Woolard, H. W.: "Thin-Airfoil Theory of an Ejector-Flapped Wing Section," AIAA 74-187, February 1974.
- Proceedings of the NASA/NADC/AFFDL Workshop on Thrust Augmenting Ejectors, NASA CP-2093, September 1979.
- Summary Report, XfV-12A Diagnostic and Development Program, Rockwell International, October 1981.
- Catalano, G. D.; Nagaraja, K. S.; Wright, H. E.; and Stephens, D. G.: "Turbulence Measurement in an Ejector Wing Flow Field," AIAA 81-1712, August 1981.
- Porter, J. L.; and Squyers, R. A.: "Ejector Wing Design," Air Force Wright Laboratories Report AFWAL-TR-82-3011, September 1981.
- Anderson, S. B.; and Faye, A. E. Jr.: "Flight Investigation of the Low Speed Characteristics of a 35 Degree Swept-Wing Airplane Equipped with an Area-Suction Ejector Flap and Various Leading Edge Devices," NACA-RM-A57G10, September 1957.
- Fishbach, L. H.: "Performance of Ejector Wing Aircraft for Navy VTOL Fighters," NASA TM X-68237, May 1973.
- Squyers, R. A.; Porter, J. L.; Nagaraja, K. S.; and Cudahy, G. F.: "Ejector Powered Propulsion and High Lift Subsonic Wing," ICAS 82-6.5.2.
- Domalski, J. T.: "Theoretical Determination of the Lift of a Simulated Ejector Wing," M.S. Thesis, Air Force Institute of Technology, December 1982.
- Flinn, E.: "Tests of Ejector Pump Configurations Designed for Use in the Ejector Flap Boundary Layer Control System," WADC Technical Note 55-29, Wright Air Development Center, Dayton, OH, August 1957.
- Lowry, J. G.; Riebe, J. M.; and Campbell, J. P.: "The Jet-Augmented Flap," Institute of the Aeronautical Sciences Paper No. 715, January 1957.
- Deckert, W. H.; and Franklin, J. A.: "Powered-Lift Aircraft Technology," NASA SP-501, 1989.
- Deckert, W. H.; and Franklin, J. A.: "Powered Lift Technology on the Threshold," *Aerospace America*, Vol. 23, No. 11, November 1985.
- Riley, D. R.; Croom, M. A.; and Shah, G. H.: "Wind-Tunnel Free-Flight Investigation of an E-7A STOVL Fighter Model in Hover, Transition, and Conventional Flight," NASA TP 3076, April 1991.

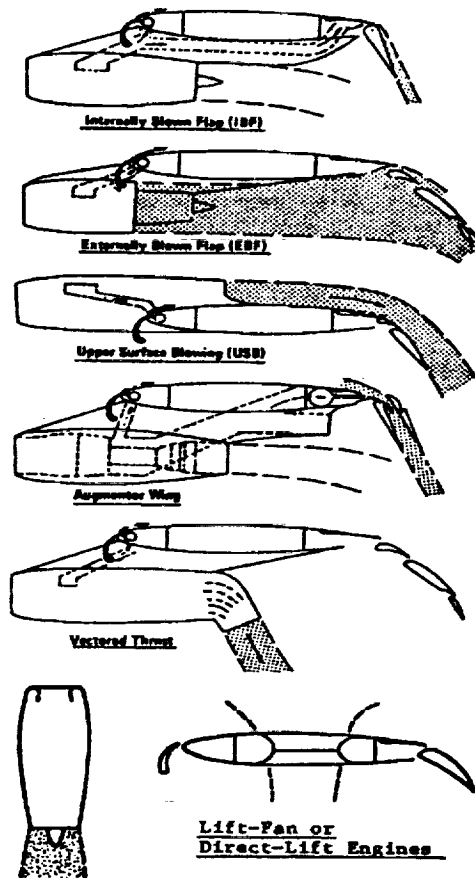


Figure 1. Powered Lift Concepts, from ref. 1.

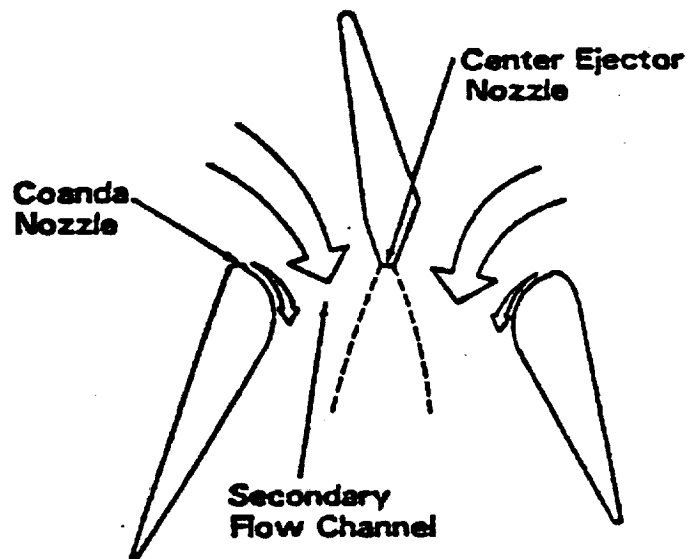


Figure 2. Typical ejector augmentor cross section for augmentor wing, from ref. 2.

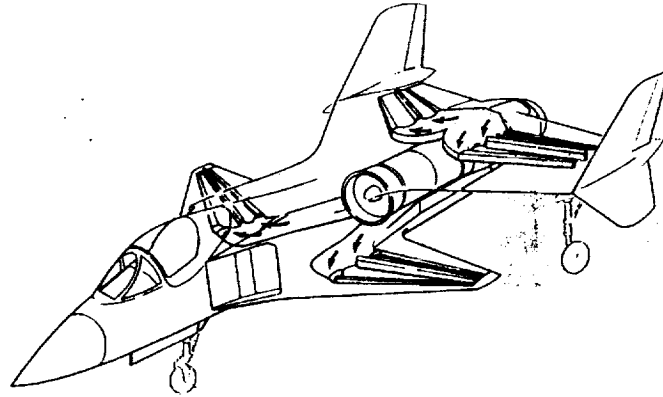


Figure 3. Propulsion system and augmentor flow for vertical lift, from ref. 2.

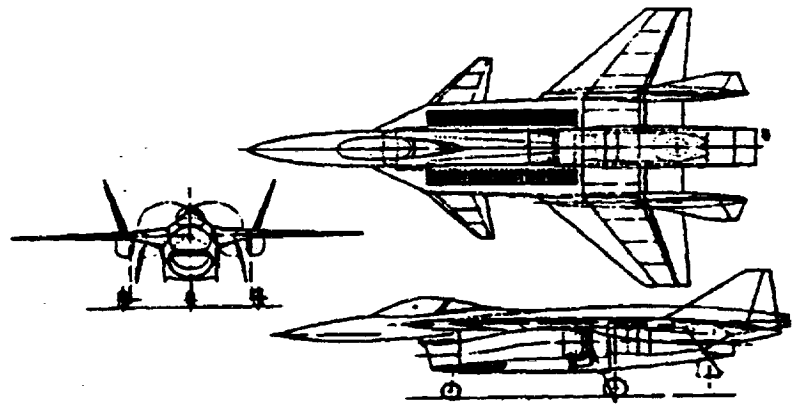


Figure 4. Ejector lift/vectored thrust concept combat aircraft, from ref. 3.

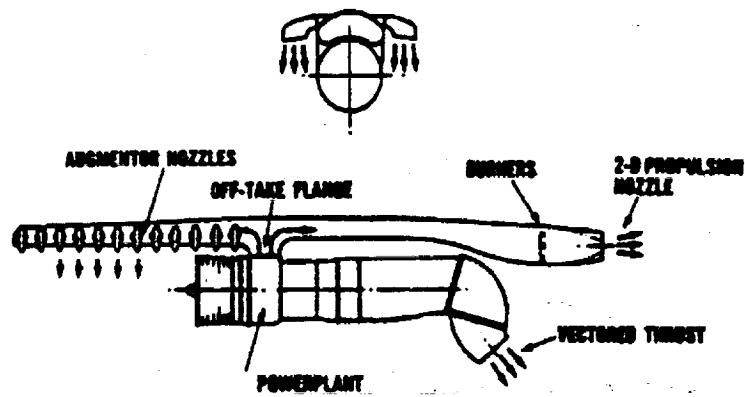


Figure 5. Deployment of jet flow for short takeoff, from ref. 3.

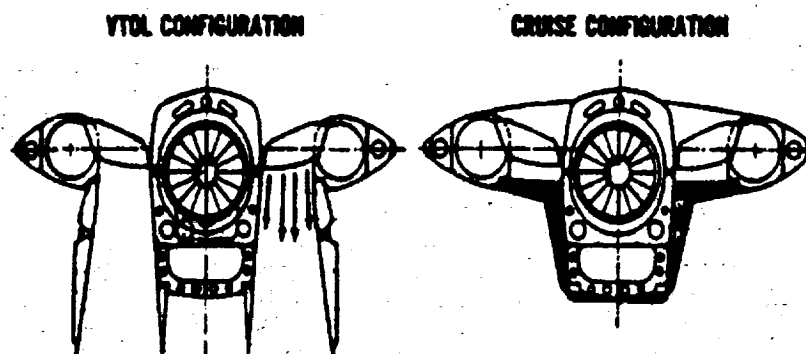


Figure 6. Cross section of ejector system, from ref. 3.

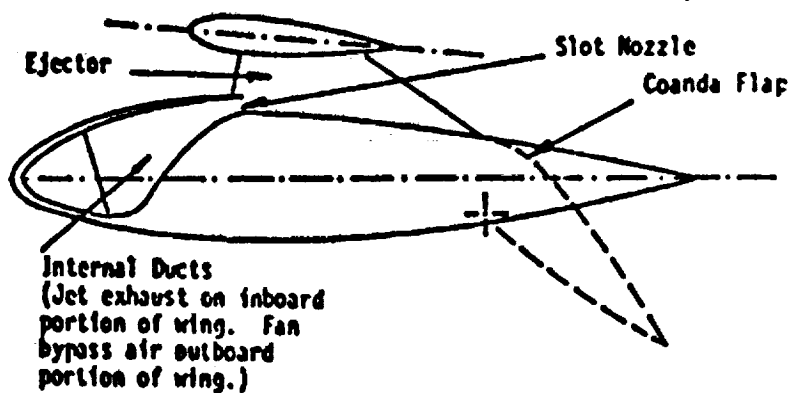


Figure 7. Two dimensional view of Jetwing concept with ejector installed, from ref. 4.

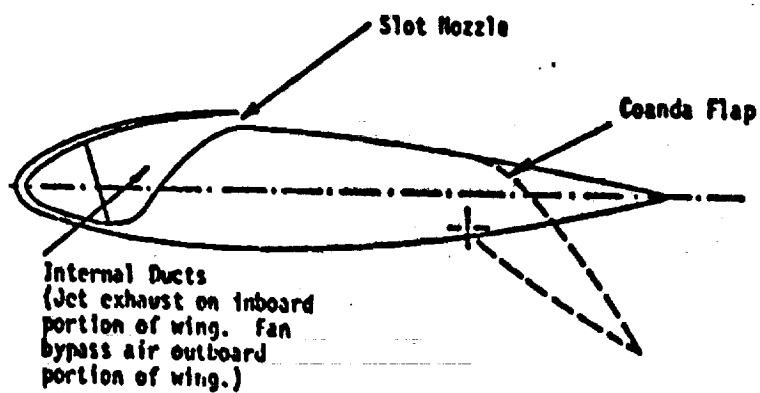


Figure 8. Two dimensional view of Jetwing concept without ejector installed, from ref. 4.

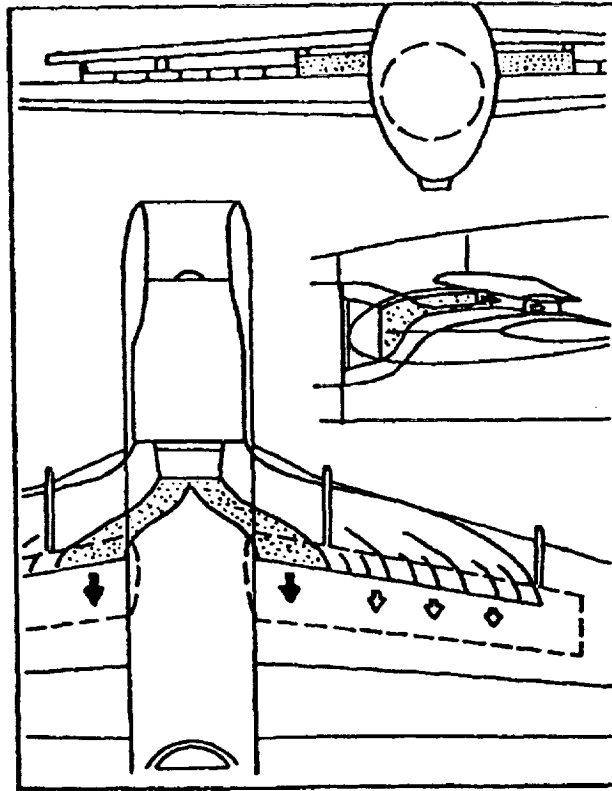


Figure 9. Jetwing ducting arrangement, from ref. 1.

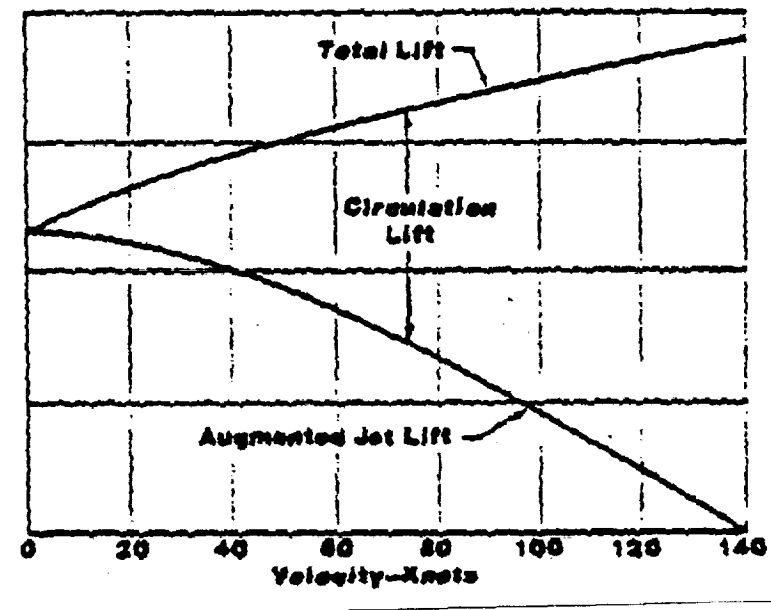


Figure 10. Increased STOL total lift with vectored augmentor, from ref. 2.

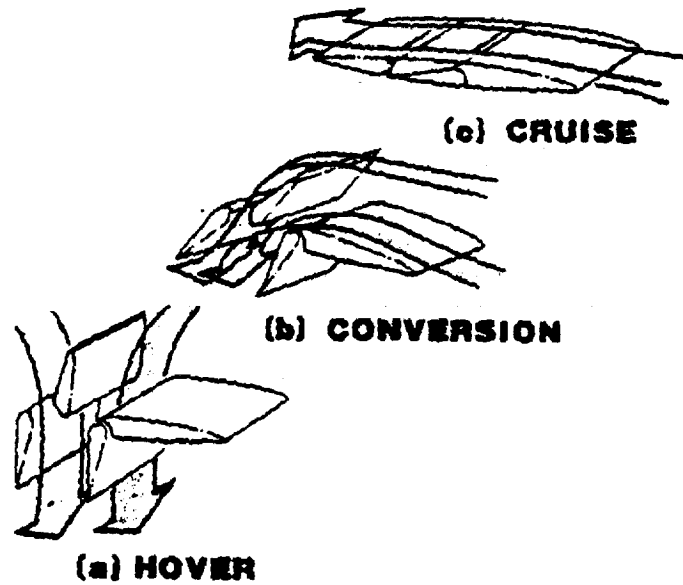


Figure 11. Thrust augmented wing in hover, transition/STOL, and conventional flight, from ref. 2.

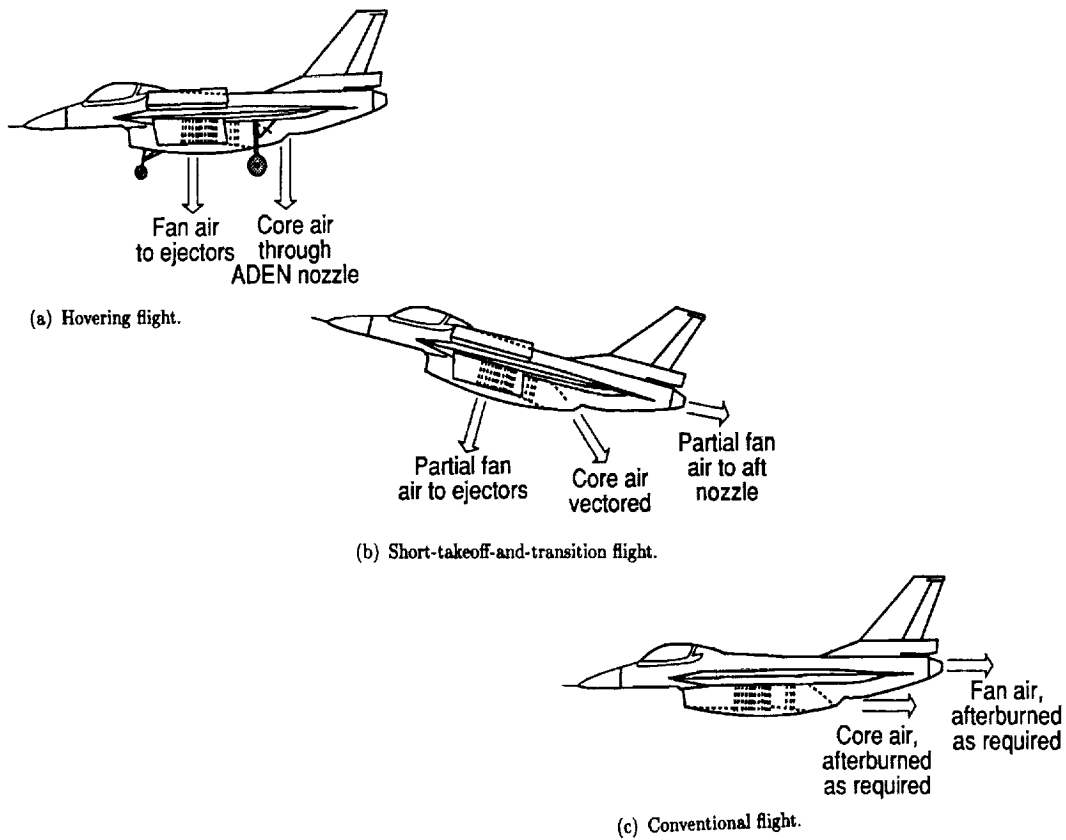


Figure 12. Modes of operation of the E-7A, from ref. 5.

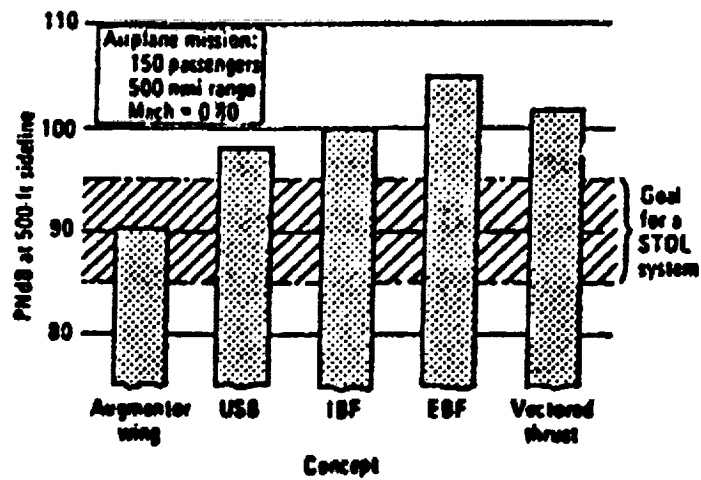


Figure 13. Noise levels for powered lift concepts, from ref. 1.

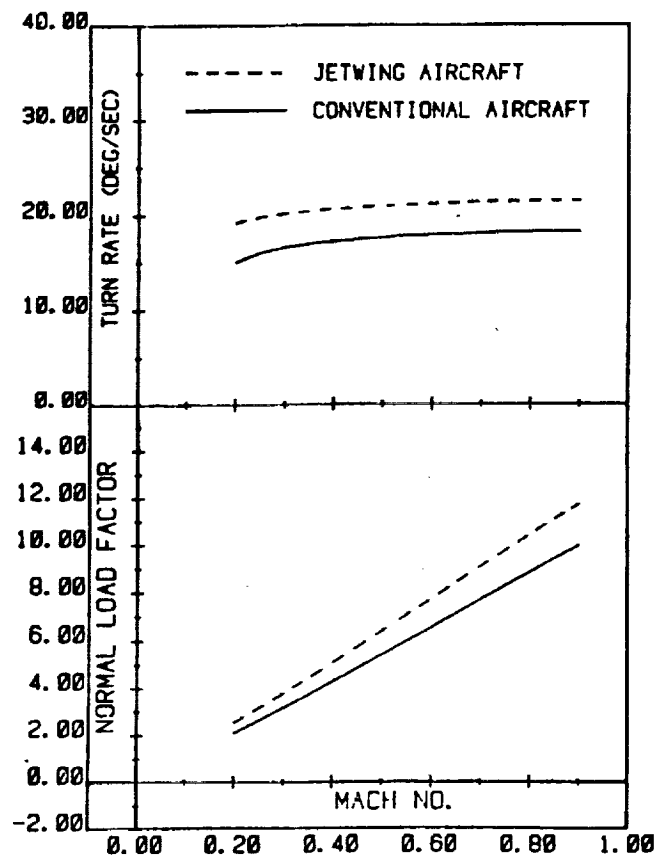


Figure 14. Sustained maneuver performance with afterburner at sea level, from ref. 1.

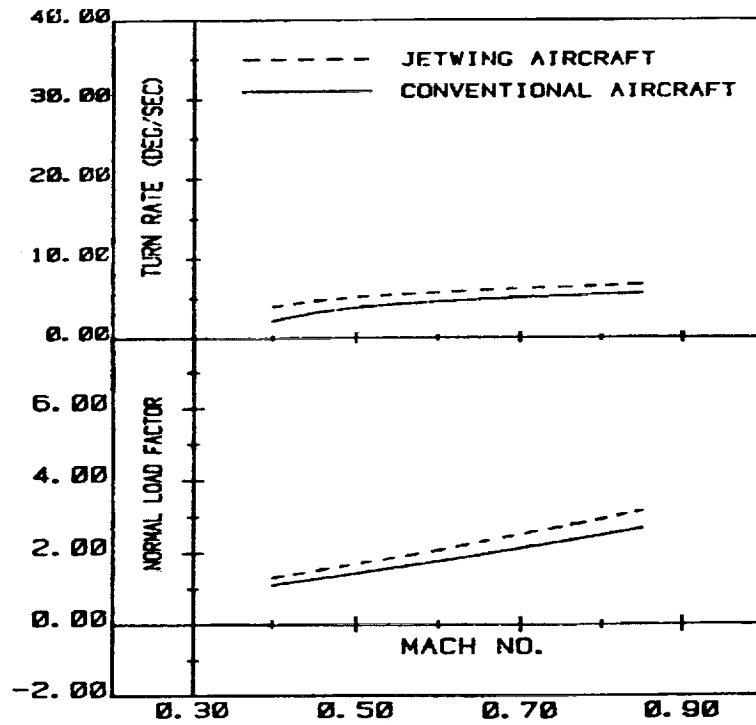


Figure 15. Sustained maneuver performance with afterburner at 35000 ft. altitude, from ref. 1.

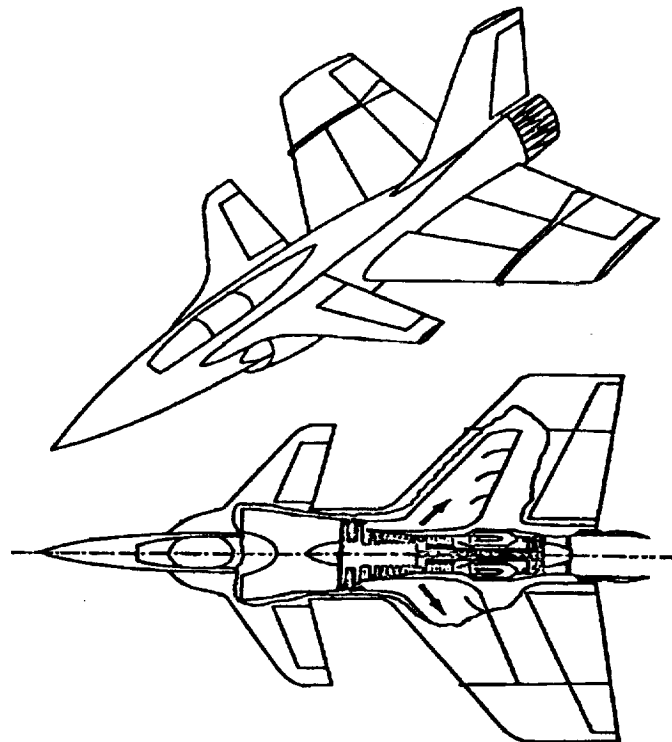


Figure 16. Attack aircraft based upon Jetwing concept, from ref. 1.

Wing-Tip Modifications

Blowing

Technology Concept. Wingtip blowing entails exhausting one or more jets of air from the wingtip in a generally spanwise direction. Air for the jet can be bled from the propulsion system, removed from the flow at the aircraft surface by a laminar-flow-control system, or ducted from the region of the stagnation line along the wing leading edge. Figure 1 shows two different blowing configurations, blowing from a long-chord slot and blowing from multiple short-chord slots. This figure and much of the following discussion is summarized from reference 1.

References 2 to 5 describe some early work in this area. These studies considered low-aspect-ratio wings, large jet momentum coefficients, and jet chords that were a large fraction of the wingtip chord. The results of these studies were that lift-curve slope could be increased and that blowing increased the loading across the span with the largest increases occurring near the tip. Blowing also increased the maximum lift coefficient. Flow surveys downstream of the wing with and without blowing indicated that blowing displaced the primary wingtip vortex outward and upward, diffused the vortex over a larger area, and reduced maximum vorticity at the center of the vortex. These studies used jet momentum coefficients ranging from 0.10 to 1.75. These values were much larger than the typical thrust to dynamic pressure-wing area ratios of transports of 0.04.

The more recent work found in references 6 to 8 made use of several short-chord jets, more realistic blowing coefficients typically between 0.001 and 0.008, and low aspect-ratio wings. These studies found that blowing from several short-chord jets can produce results similar to those obtained with a single continuous jet. The magnitude of the effects are proportional to the blowing coefficient.

One of the most recent and exhaustive investigations into this concept is presented in reference 1. This study differed from earlier efforts in that a larger aspect-ratio wing was tested and corresponding Navier-Stokes analyses were performed. The findings of this study were that for moderate aspect-ratio wings at high subsonic Mach numbers the benefits of spanwise blowing were quantifiable.

Benefits. Wing tip blowing can improve the aerodynamic performance of wings. The main effects of spanwise blowing are to increase the wing effective aspect ratio and to increase the loading towards the wing tips. Thus, wing tip blowing provides effects that are similar to those of winglets, but the blowing can be tailored to improve performance of the aircraft throughout its mission instead of just one design point. In addition, wingtip blowing can be used asymmetrically to provide roll and lateral control of the aircraft. Finally, wing-tip blowing may help to diffuse the wingtip vortex which can potentially make airport operations more efficient by allowing reduced aircraft separation.

Wing tip blowing has some limitations and penalties. It provides the greatest benefit for low aspect-ratio wings. Consequently, it may not be applicable to subsonic transports. It adds complexity and weight like other internal flow blowing systems, and the jet momentum coefficients required to achieve aerodynamic benefits may impose large engine performance penalties.

Applications. Wing tip blowing has not been applied to any aircraft, production or experimental. The concept performs better on low aspect ratio configurations so single stage to orbit or high speed civil transport vehicle designs may benefit from this technology. If wing tip blowing were considered as part of a larger system like suction boundary layer control, then it may have potential in other configurations.

References.

1. Mineck, R. E.: "Study of Potential Aerodynamic Benefits From Spanwise Blowing at the Wingtip," NASA TP 3515, June 1995.

2. Tavella, D. A.; Wood, N. J.; Lee, C. S.; and Roberts, L.: "Two Blowing Concepts for Roll and Lateral Control of Aircraft," NASA CR 180478, October 1986.
3. Ayers, R. F. and Wilde, M. R.: "An Experimental Investigation of the Aerodynamic Characteristics of a Low Aspect Ratio Swept Wing with Blowing in a Spanwise Direction from the Tips," The College of Aeronautics Cranfield, September 1956.
4. Smith, V. J.; and Simpson, G. J.: "A Preliminary Investigation of the Effect of a Thin High Velocity Tip Jet on a Low Aspect Ratio Wing," Note ARL/A.163, Australia Dep. of Supply, June 1957.
5. Lloyd, Adrian: "The Effect of Spanwise Blowing on the Aerodynamic Characteristics of a Low Aspect Ratio Wing," von Karman Institute for Fluid Dynamics Project Report 1963-90, 1963.
6. Wu, J. M.; Vakili, A. D.; and Chen, Z. L.: "Wing-Tip Jets Aerodynamic Performance," 13th Congress of the International Council of the Aeronautical Sciences, AIAA Aircraft Systems and Technology Conference, Seattle, Washington, August 1982.
7. Wu, J. M.; Vakili, A. D.; and Gilliam, F. T.: "Aerodynamic Interactions of Wingtip Flow with Discrete Wingtip Jets," AIAA 84-2206, August 1984.
8. Wu, J. M.; Vakili, A.; Chen, Z. L.; and Gilliam, F. T.: "Investigation on the Effects of Discrete Wingtip Jets," AIAA 83-0546, January 1983.

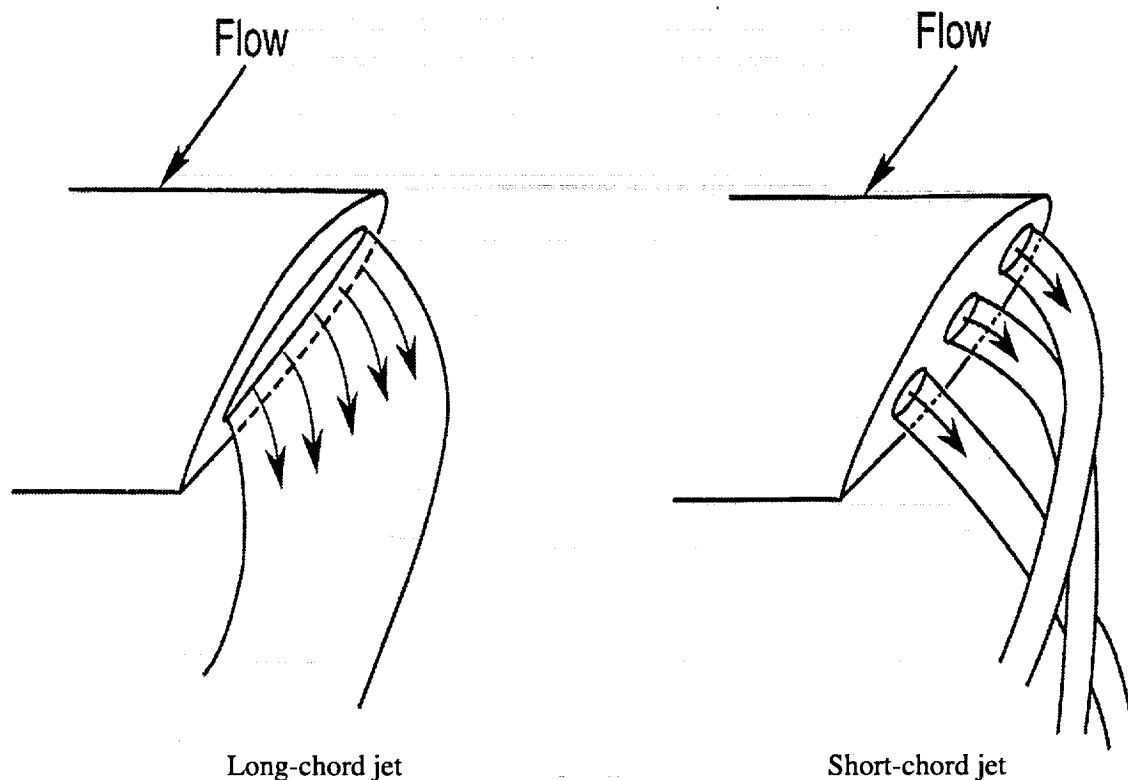


Figure 1. Wingtip blowing configurations.

Engines/Turbines

Background and Technical Description. There has been an awareness for a long time of the large amount of energy present in the tip vortex that is shed from an aircraft wing during flight, as shown in figure 1. Devices to harness this energy usually come in three main forms: static, propulsive, and generative. Although the detailed analyses involved in the flow phenomena are quite complex, the basic concepts are straightforward.

Many static additions, some of which are shown in figure 2, have been proposed for the wing tips. These devices interrupt the formation of the wing-tip vortex, thus reducing the induced drag of the configuration. The most well-known example of the static device, however, is the winglet. In addition to reducing the formation of the wing-tip vortex, the design and placement of the winglet utilizes the local components of lift and drag at the wing tip to create a net increase in aircraft thrust. That winglets are successful in this task is apparent in the number of aircraft that now use them. For this reason, they are not covered in this summary of wing-tip devices.

Mounting propulsive devices on the wing tips has been considered since the early 1960's for purposes of extracting additional energy from the tip vortex. Devices that have been analyzed and tested in the past include tractor propellers [refs. 1 and 2], pusher propellers [refs. 3 and 4], and fan-jets [ref. 5]. All of them rely on using the already-rotating vortex to lessen the necessary rotation of the engine to provide a certain level of thrust, and it is for this reason they all rotate counter to the direction of the vortex, figure 3.

In the 1980's there appeared a great deal of interest in the third type of device, generative, which is usually referred to as a wing-tip vortex turbine [ref. 6]. These devices are essentially passive, as they are driven by the wing-tip vortex flow, with the resulting energy of the turbine to be used for pneumatic, hydraulic, or electrical purposes. As they are driven by the wing-tip vortex, they rotate in the same direction, figure 4.

Benefits. If propellers are mounted on the aircraft wing tips, rotating in a direction opposite to that of the wing-tip vortex, there is an increase in the net thrust minus drag of the configuration. According to reference 7, the reduction in the power required to maintain a given flight condition is the same for both tractor and pusher configurations, but for different reasons. In the case of a tractor propeller, the thrust of the propellers will be the same as an isolated propeller, but the induced drag of the wing behind the propeller will be less than the induced drag of the wing in isolation. In the case of pusher propeller, the induced drag of the wing will remain the same, but the thrust of the propeller will be greater than the thrust produced in isolation. Both improvements are essentially equal. The amount of thrust increase and drag decrease is highly configuration-dependent, but it can be significant.

If the fan-jet is mounted on the wing tip, then the effect of its rotating parts interacting with the vortex flow is significantly reduced because of the recessed location of the rotating parts within the nacelle and the forward placement of the fan-jet relative to the wing tip. In addition, the nacelle shape itself may actually increase the vortex strength. The prime benefit from a fan-jet installation on the wing tip is due to its non-rotating engine exhaust, which tends to dissipate the wing-tip vortex, thus reducing induced drag.

When considering the wing-tip vortex turbine, it is interesting to consider this passive device in the limiting case of zero rotation (if it is locked into position) as a static device, like an end plate. In this configuration, reduction of the induced drag is the only effect of the turbine. In normal operation the pitch of the turbine blades can be changed, altering the percentage of energy extracted that goes to the turbine. The wing-tip turbine is thus capable of a continuous trade-off of rotational energy extracted from the flow versus reduction of induced drag. This capability makes it a convenient device for supplying power or reducing drag, whatever is needed within the flight envelope. Flight test data [ref.8] from a small aircraft, a Piper PA-28 shown in figure 5, scaled theoretically to the size of a medium transport,

have shown that the amount of vortex energy recovered by the wing-tip vortex turbine may be sufficient to generate the power required by an all electric aircraft system or a boundary layer control system [ref. 8]. The energy extracted from the wing-tip vortex does not need to be converted to electric power necessarily, as it may be used to develop pneumatic or hydraulic pressure directly.

All of the above devices that alter the vortex motion also have the advantage that, by doing so, they reduce the hazard to other aircraft due to this vortex. This is especially true near airports, where tip vortex effects and airplane traffic are at a maximum. Propulsive devices mounted on the wing tips, farther away from the fuselage than usual, would also be useful in reducing cabin noise levels.

Present and/or Past Utilization. There are no examples of any production configurations that have utilized either propeller or fan-jet engines at the wing tip for the purposes of altering the wing-tip vortex structure and extracting flow energy more efficiently. Current tilt-rotor designs tend to have their engines more outboard than usual, but this is done to ensure the clearance between the inordinately large propellers and the fuselage. The general feeling seems to be that putting the engines so far out would reduce the engine-out safety capabilities of the aircraft, as well as introduce a number of stability and control, aeroelasticity, structural design, and fabrication problems. The structural design problems may be alleviated using the concept of a truss-braced wing, which is currently being studied [ref. 9].

Although the wing-tip vortex turbine has not been used on a production aircraft, there seems to be more interest in this concept recently. Fairly recently, Airbus Industrie showed some interest in this device to be used as a winglet in the locked position during normal flight. It would then be released to provide electrical power in an emergency [ref. 10]. It was calculated that the vortex turbine could provide more than twice the power of a conventional ram-air turbine. This effort has been joined recently by Sundstrand Aerospace [ref. 11].

Applications and Configuration Integration. Although propulsive wing-tip devices have been shown to possess several advantages over their more conventionally-mounted counterparts, it remains to be seen whether the stability and control, aeroelasticity, structural design, and fabrication problems can be overcome. By far the most optimistic approach, and one that future applications may be based on, is with the truss-braced aircraft. There may also be a synergism between the thick Blended-Wing-Body concept and the placement of the propulsive units. If such a thick airfoil becomes desirable, then the Goldschmied Airfoil concept might also fit well into an integrated configuration.

Wing-tip Vortex Turbines seem to be more easily integrated into existing aircraft and future concepts. The idea of getting power from energy that would normally be left in the airstream is attractive, not to mention that any power extracted would make air traffic that much safer in the area. This power could be used as electricity for routine, backup, or emergency purposes. Instead of converting the vortex energy into electrical power, however, it could be used as pneumatic power as a supply for a boundary layer control system, for example. If it is converted into hydraulic power, it could be used to power flaps or some sort of active airfoil shaping system. The relative simplicity of a generative wing-tip system compared to a propulsive wing-tip system makes it that much more attractive.

References.

1. Snyder, Melvin H., Jr.; and Zumwalt, Glen W.: "Effects of Wingtip-Mounted Propellers on Wing Lift and Induced Drag," *J. Aircraft*, Vol. 6, No. 5, September-October 1969.
2. Loth, J. L.; and Loth, F.: "Induced Drag Reduction with Wing Tip Mounted Propellers," AIAA 84-2149, August 1984.
3. Patterson, J. C.; and Bartlett, G. R.: "Effect of a Wing-Tip Mounted Pusher Turboprop on the Aerodynamic Characteristics of a Semi-span Wing," AIAA 85-1286, July 1985.
4. Patterson, James C., Jr.; and Bartlett, Glynn R.: "Evaluation of Installed Performance of a Wing-tip-mounted Pusher Turboprop on a Semispan Wing," NASA TP 2739, 1987.

5. Patterson, James C., Jr.; and Flechner, Stuart G.: "An Exploratory Wind-Tunnel Investigation of the Wake Effect of a Panel Tip-Mounted Fan-Jet Engine on the Lift Induced Vortex," NASA TN D-5729, 1970.
6. Patterson, James C., Jr.; and Flechner, Stuart G.: "Exploratory Wind-Tunnel Investigation of a Wingtip-Mounted Vortex Turbine for Vortex Energy Recovery," NASA TP 2468, 1985.
7. Miranda, Luis R.; and Brennan, James E.: "Aerodynamic Effects of Wingtip-Mounted Propellers and Turbines," AIAA 86-1802, June 1986.
8. Abeyounis, William K.; Patterson, James C., Jr.; Stough, H. Paul, III; Wunschel, Lt. Col. Alfred J.; and Curran, Patrick D.: "Wingtip Vortex Turbine Investigation for Vortex Energy Recovery," SAE Technical Paper 901936, 1990.
9. Asbury, Scott C.: "DDF Proposal for Truss-Braced Wing Aircraft (Phase II)," NASA Langley Research Center, June 1996.
10. *Flight International*, 21 October 1989, p. 31.
11. Kroll, William B.: *1995 Annual Report, Vortex Turbine*. Sundstrand Aerospace, October 1995.

Bibliography.

- Schaffer, A.: "A Study of Vortex Cancellation," *J. Aerospace Sciences*. Vol. 27, No. 3, March 1960, p. 193.
- Snyder, M. H.: "Effects of Wingtip-Mounted Propeller on Wing Lift Induced Drag and Shed Vortex Pattern," Ph.D. Thesis, Oklahoma State University, May 1967.
- Patterson, James C., Jr.; Hastings, E. C., Jr.; and Jordan, F. L., Jr.: "Ground Development and Flight Correlation of a Vortex Attenuating Spline Device," NASA SP 409, September 1972.
- Patterson, J. C., Jr.: "Lift-Induced Wing-tip Vortex Attenuation," AIAA 74-0038, January 1974.
- Patterson, James C., Jr.: "Vortex Attenuation Obtained in the Langley Vortex Research Facility," *J. Aircraft*, Vol. 12, No. 9, September 1975, pp. 745-749.
- Patterson, James C., Jr.; and Jordan, Frank L.: "Thrust-Augmented Vortex Attenuation," NASA SP-409, February 1976.
- "Wingtip-Vortex Turbine Lowers Aircraft Drag," *NASA Tech. Briefs*, Summer 1981.
- "Turbines Recover Power by Dissipating Induced Drag from Wingtip Vortices," *Aviation Week & Space Technology*, September 1, 1986, p. 199.
- "Wing-tip dynamos spin out extra power," *Popular Science*, September 1987.
- Patterson, J. C., Jr.; and Abeyounis, W. K.: "Wingtip Vortex Turbine Investigation Vortex Energy Recovery," Vu-graphs from a presentation at the International Aviation Convention; Lakeland, Florida; April 1991.

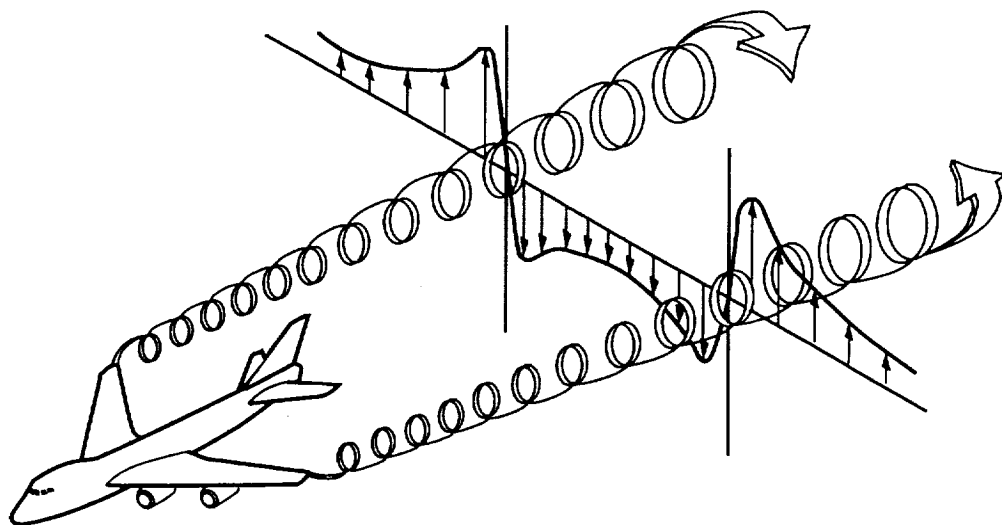


Figure 1. Downstream velocity distribution of an aircraft, from ref. 8.

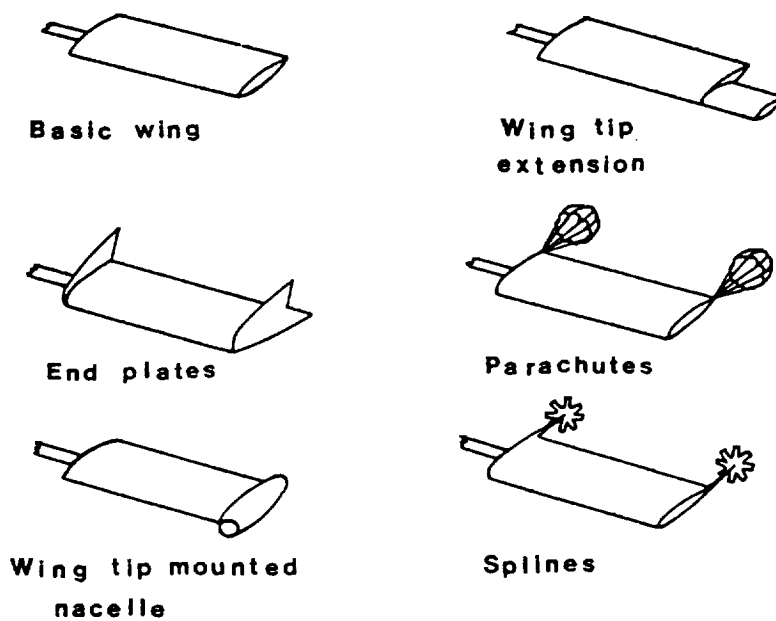


Figure 2. Techniques used to lower the trailing-vortex velocity, from ref. 2.

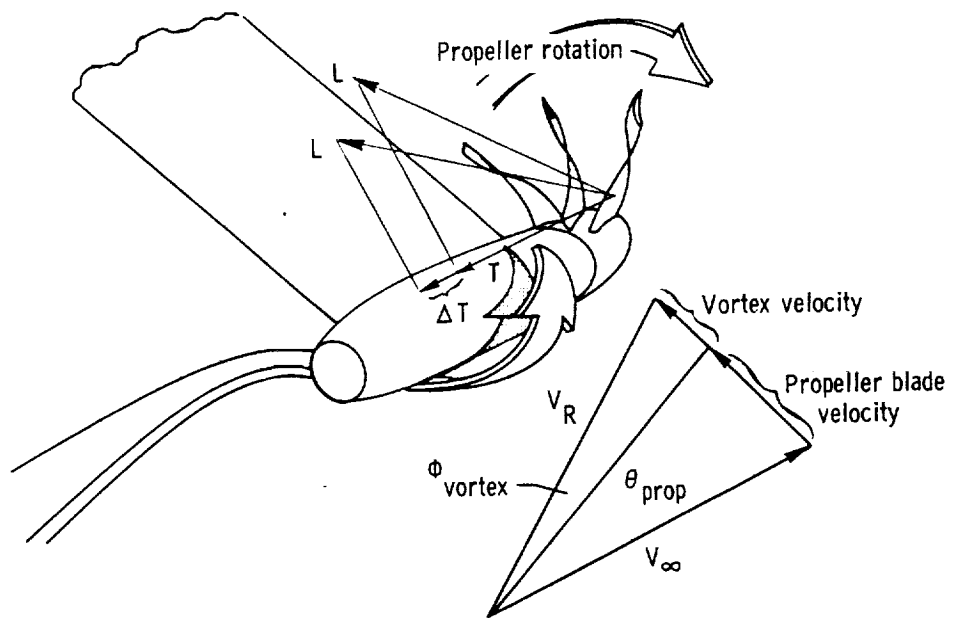


Figure 3. Change in velocity components due to vortex flow, from ref. 4.

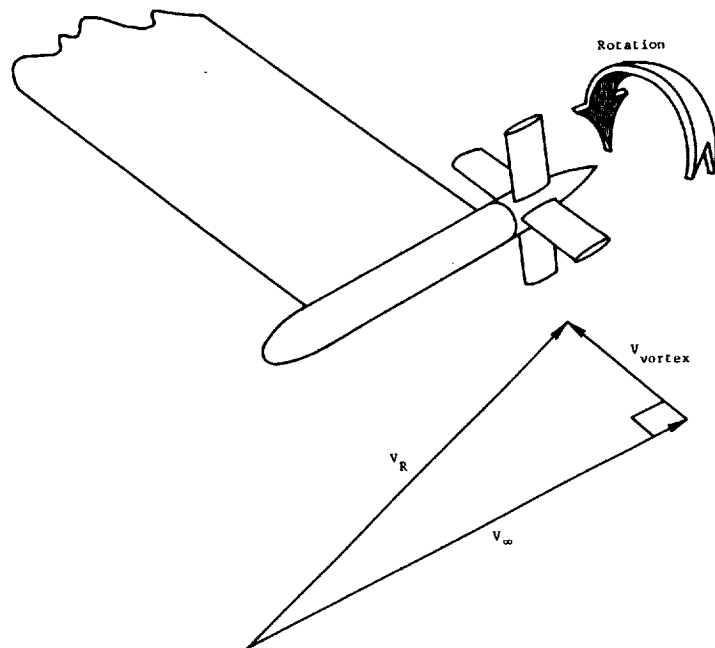


Figure 4. Vortex and stream flows and the resulting velocity, from ref. 6.

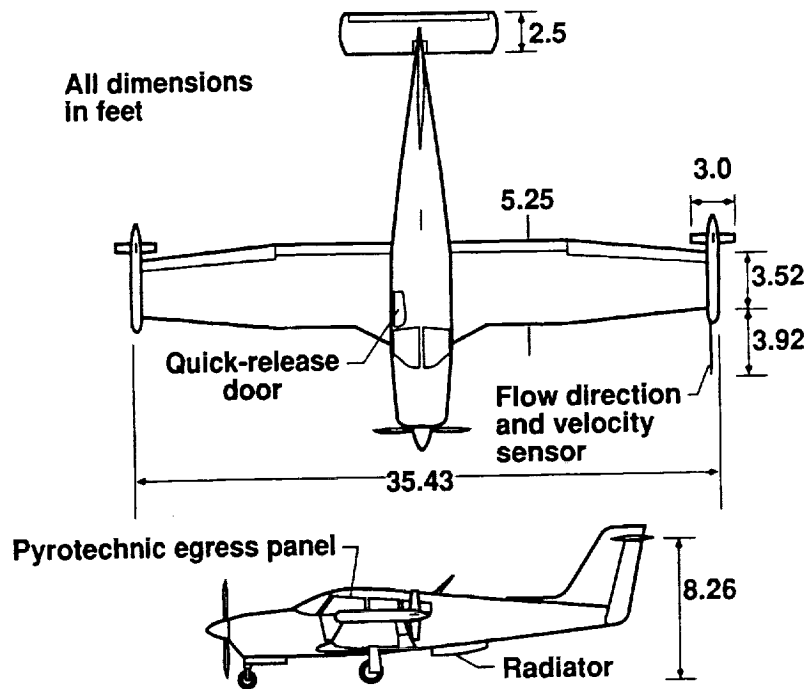


Figure 5. Test aircraft with vortex turbines on both wingtips, from ref. 8.

Methods of Increasing Cruise Efficiency

Goldschmied Airfoil

Background and Technical Description. (The final co-op report by J. M. (Farrah) Elliott [ref. 1] was used to extract much of the salient information presented below. That paper is to be consulted by the reader who is interested in a complete background summary of boundary-layer-controlled thick-suction airfoils.)

The idea of using laminar-flow airfoils with the associated low-drag benefit has been a long-held goal of aerodynamicists [ref. 2]. In fact, some recent flight studies of current business and commuter transport airplanes "suggest that significant regions of natural laminar flow exist and that this boundary-layer behavior is more persistent and durable on certain practical production airplane surfaces than previously expected" [ref. 3]. However, these regions are not full-chord and do not encompass the entire span. Early directed efforts at achieving natural laminar flow on aircraft was toward fighters [ref. 4] with thin airfoils of the NACA series of laminar-flow airfoils developed before and during World War II. However, applications of laminar flow to thicker section have also been considered. Among those doing this was A. A. Griffith of the Aeronautical Research Council in the U.K. in the 1940s, who suggested designing an airfoil with a velocity gradient along the chord that is boundary-layer stabilizing and favorable, except at one place along the airfoil where a velocity-discontinuity and a sharp-pressure-rise occur. (Some boundary-layer suction may be needed in order to achieve the extent of laminar flow desired on both thick- and thin-airfoil sections.) This suggestion has been experimentally investigated by Richards and Burge in reference 5 and an example is shown in figure 1. Applying boundary-layer suction in the required amount at a location just ahead of the occurrence of velocity discontinuity could result in a downstream flow which is not separated.

An application of boundary-layer suction was envisioned by Goldschmied in the 1950's as applied to airships. Later testing by Goldschmied [ref. 6] found that a self-propelled streamlined body with boundary-layer suction in the aft region worked well (see fig. 2); in particular, the combination of suction, a proper suction slot, an aft-mounted external-truncated-conical-ring (i.e., the Ringloeb cusp), and a tailboom. He also found that in order for the boundary-layer control to be integrated with the propulsion system of a vehicle, two conditions must be met. The levels of suction have to be the minimum to keep the flow attached, and the thrust of the stern jet must be equal to the sum of the wake drag and the suction momentum drag. In the tests with the integrated hull of a typical airplane, Goldschmied successfully showed that a large power gain could be achieved by integrating boundary-layer control with static-pressure propulsion [ref. 7]. He subsequently proposed the application of this concept to airfoils/wings [ref. 8].

Benefits and Research Opportunities. The use of boundary-layer suction for propulsion was put forward by Kuchemann and Weber [ref. 9] in that one could consider an "...extreme application of boundary-layer suction, which uses air from the boundary-layer on the aircraft surfaces as working air for the engine and restores it to full free-stream energy, instead of producing a thrust force to overcome the drag associated with the wake."

With the use of suction to control the boundary layer through slots and then using that air to provide static-pressure propulsion by means of a combination suction/blower, this concept will have a 50% reduction in power required for an integrated hull [ref. 10] at cruise. In addition, there will be a corresponding reduction in the thrust required and so the noise will also be reduced. This is because the air noise from a conventional fuselage can be reduced due to the propulsive system capturing most of the pressure fluctuations. Figure 3 shows how Goldschmied [ref. 11] proposed to do this on a small general aviation aircraft. He claims that by keeping the thrust coefficient about 0.025 and adjusting the gross weight of the aircraft against the speed and the volume of the fuselage, an aerodynamic efficiency index

$[(\text{Gross Weight}) \times (\text{Free Stream Velocity}) / (\text{Fan Shaft Power} \times 550)]$ of at least 12.0 can be achieved. These large benefits need to be substantiated independently. Wings should also see reductions in wake drag with this system at cruise, but it needs to be validated. Moreover, there is research taking place to systematically quantify the aerodynamic benefits claimed. The recent work is being lead by J. P. Sullivan of Purdue University and has so far resulted in one paper [ref. 12]. This paper reports the results of a wind-tunnel experiment to test the suction portion of the idea and develop the detailed bookkeeping needed for thrust/drag. The resulting calculated section drag coefficients are reported to agree with past experiments [ref. 13]. Follow-on studies are planned to test the combination of suction/blowing.

Other areas to be researched and/or validated are ways to address the following items: high transonic drag on this thick wing; reduced critical Mach number; duct losses in the boundary-layer control system; details of how to integrate the suction/blower with the airframe; and details of how to integrate the external propulsion system with the airframe and suction/blower system.

Configuration Integration. Goldschmied [ref. 8] proposed for his spanloader (fig. 4) that the power source for the suction/blower be configuration integrated in the design. He envisioned using wing-tip mounted propellers which would rotate against the tip vortices and have a spanwise mechanical shaft that can be cross-connected between the two engines in case of engine failure.

Applications. There were/are numerous proposed applications contained in reference 1 to airships, to a glider, shown in figure 5 as taken from reference 14 to use an alternate single-slotted profile, to a spanloader/freighter, and to transonic passenger transports - of which the V-wing (fig. 6) of H. R. Chaplin [ref. 15] is an example. Other applications could be envisioned once the majority of uncertainties have been researched successfully with the risk both being more fully understood and managed.

References.

1. Elliott, J. M.: "Boundary Layer Controlled Thick Suction Airfoils," Proposed NASA TM.
2. Shapiro, A. H.: *Shape and Flow: The Fluid Dynamics of Drag*, Anchor Books - Science Study Series, Doubleday & Company, Inc., 1961, p.167.
3. Holmes, B. J.; Obara, C. J.; and Yip, L. P.: "Natural Laminar Flow Experiments on Modern Airplane Surfaces," NASA TP 2256, June 1984.
4. Anderson, J. D., Jr.: *Introduction to Flight*, McGraw Hill Book Co., 3rd ed., p.141.
5. Richards, E. J.; and Burge, C. H.: "An Airfoil Designed to Give Laminar Flow Over the Whole Surface with Boundary-Layer Suction," A.R.C. R&M 2263, June 1943.
6. Goldschmied, F. R.: "Wind-Tunnel Test of the Modified Goldschmied Model with Propulsion and Empennage: Analysis of Test Results," David W. Taylor Naval Ship R&D Center, Report ASER-CR-02-86, 1986.
7. Goldschmied, F. R.: "Aerodynamic Design of Low-Speed Aircraft with a NASA Fuselage/Wake-Propeller Configuration," AIAA 86-2693, October 1986.
8. Goldschmied, F. R.: "Thick-Wing Spanloader All-Freighter: Design Concept for Tomorrow's Air Cargo," AIAA 90-3198, September 1990.
9. Kuchemann, D.; and Weber, J.: *Aerodynamics of Propulsion*, McGraw Hill Book Co., 1953.
10. Goldschmied, F. R.: "Integrated Hull Design, Boundary-Layer Control and Propulsion of Submerged Bodies," AIAA 66-658, June 1966.
11. Goldschmied, F. R.: "On the Aerodynamic Optimization of Mini-RPV and Small GA Aircraft," AIAA 84-2163, August 1984.
12. Campbell, B. T.; White, G. R.; and Sullivan, J. P.: "Experimental Investigation of a Half-Span Boundary Layer Control Wing," AIAA 96-2422, June 1996.

13. Preston, J. H.; Gregory, N.; and Rawcliffe, A. G.: "The Theoretical Estimation of Power Requirements for Slot-suction Aerofoils with Numerical Results for Two Thick Griffith Type Sections," A.R.C. R&M 2577, June 1948.
14. Keeble, T. S.: "Development in Australia of a Thick Suction Wing," In 'Anglo-American Aeronautical Conference', Brighton, 1951, pp. 45-76J.
15. Chaplin, H. R.: "Application of Very Thick BLC Airfoils to a Flying Wing Type Transport Aircraft," SAE TP 901992, October 1990.

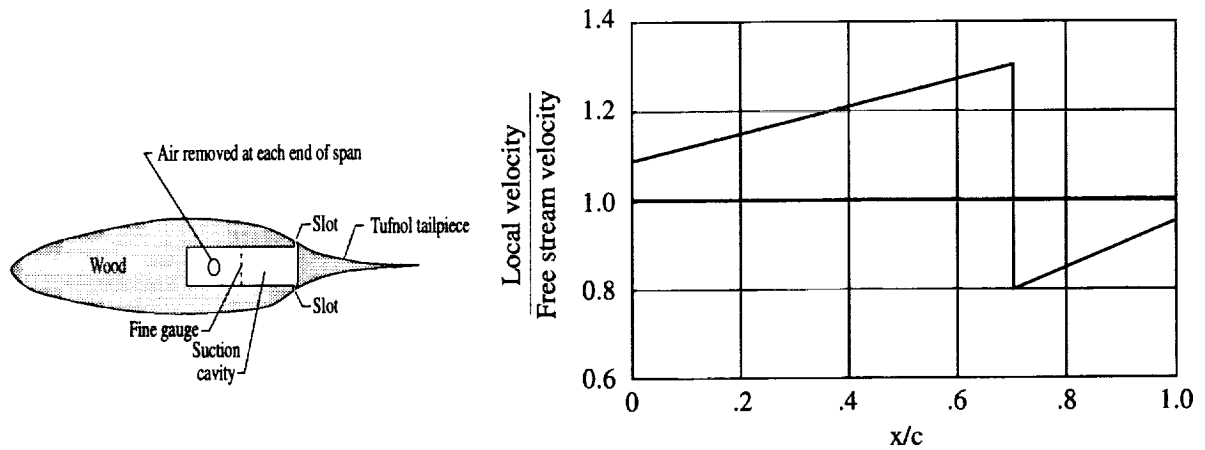


Figure 1. Profile and internal arrangement of Griffith type airfoil with boundary-layer suction and assumed airfoil velocity distribution over airfoil, from ref. 5.



Figure 2. Configuration 2 - Airship model with tailboom aftbody and empennage, from ref. 6.

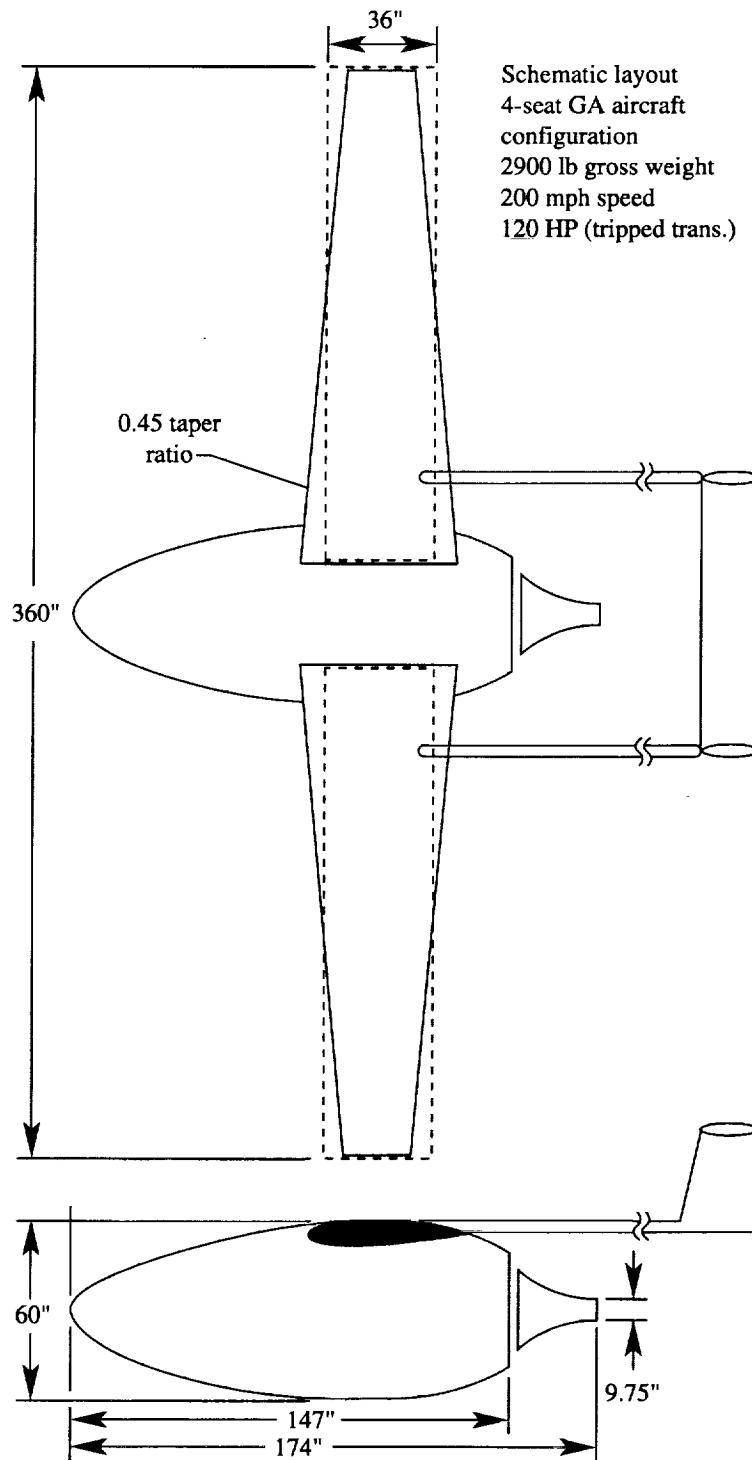


Figure 3. Four-seat GA aircraft layout, from ref.11.

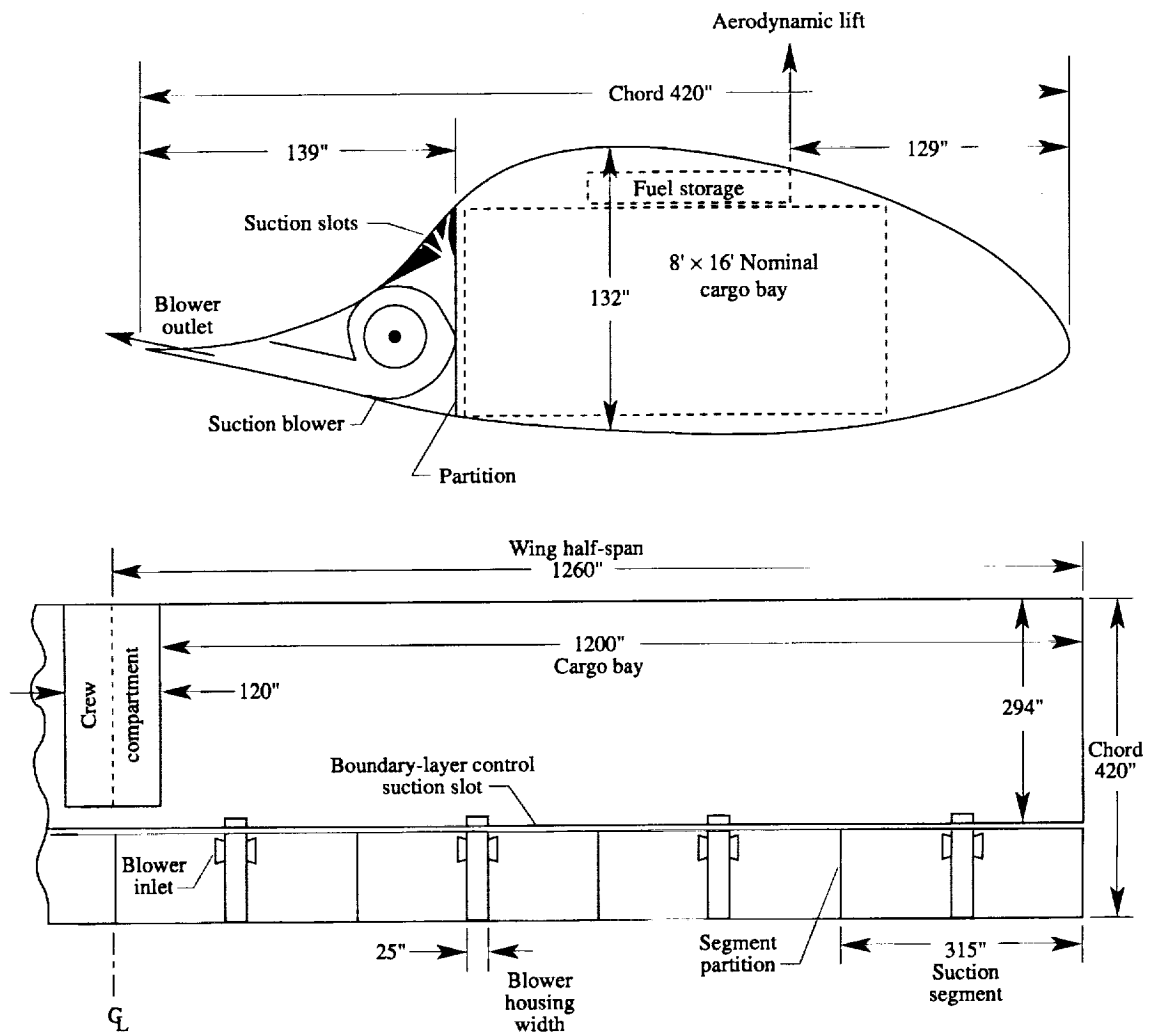


Figure 4. Goldschmied airfoil and plan view of right half of spanloader, from ref. 8.

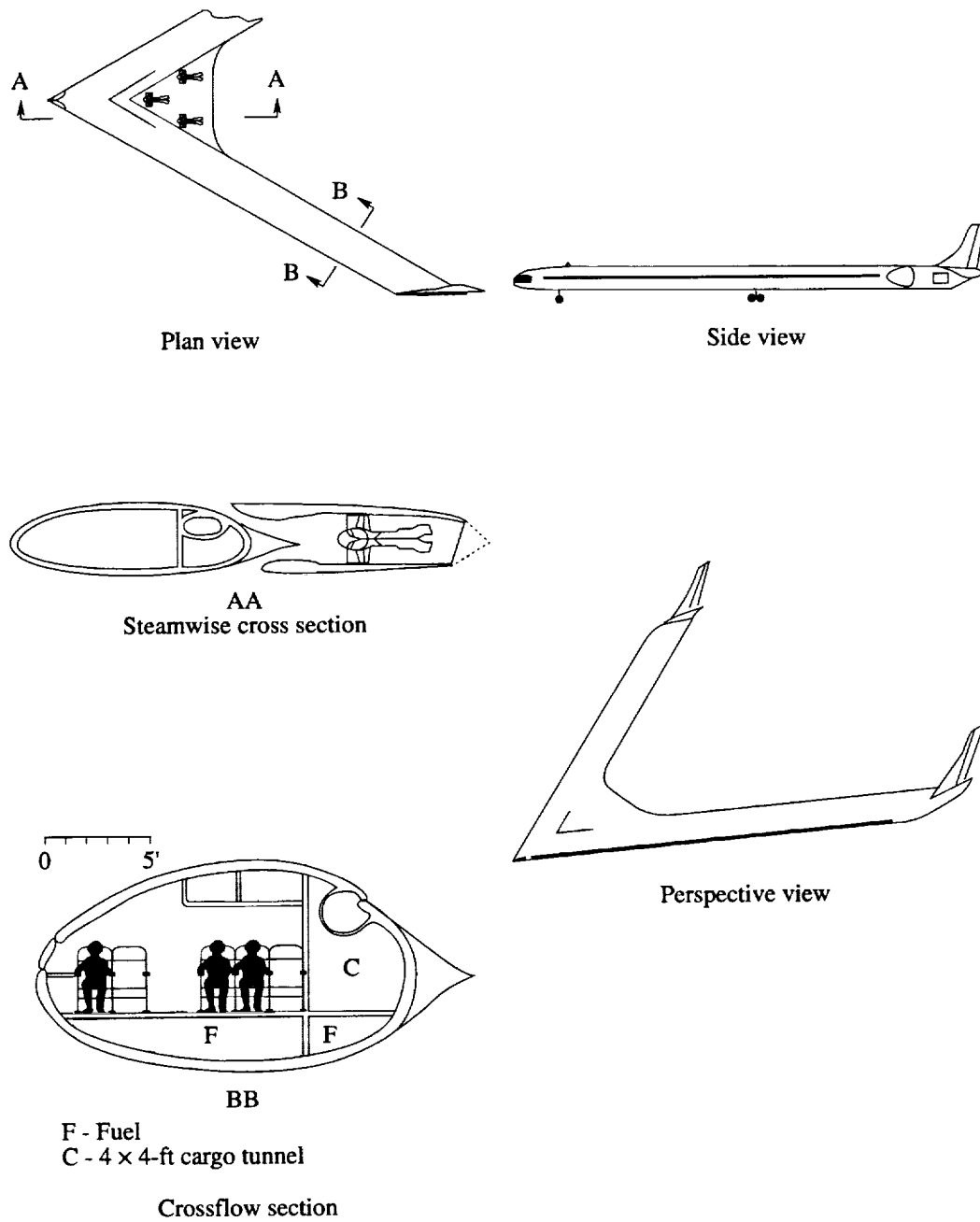


Figure 6. Chaplin V-Wing, from ref. 15.

Boundary Layer Inlet

Background and Technical Description. One of several examples of synergistic propulsion-aerodynamic interaction is the concept of the boundary layer inlet. Originally conceived for applications in marine propulsion (combat or cargo-carrying submarines, torpedoes) this approach involves the intake of the low momentum boundary layer generated on a body (fuselage or wing) to the propulsor (engine) in order to minimize losses in propulsive efficiency. Propulsive efficiency is a measure of the effectiveness of the propulsor in converting the energy of the fluid passing through the propulsor into thrust. In certain marine and in most aircraft applications it is desirable to have propulsors or engines with as high a thrust to weight ratio as possible. This requirement in turn leads to higher rotational speeds in the propulsor in order to provide a high level of thrust. The combination of small size (engine weight) and high rotational speed is connected with a corresponding loss in propulsive efficiency [ref. 1]. The boundary layer intake arrangement takes advantage of the use of the diminished inlet velocity (low momentum boundary layer fluid) to the propulsor in order to overcome some of these losses in propulsive efficiency. The amount of work required (shaft or compressor) is directly linked to the inlet velocity. Thus, by utilizing a lower inlet velocity, the amount of work required is diminished, and therefore, the propulsive efficiency of the engine is increased. The theoretical analysis of the boundary layer intake is presented in detail in references 1 and 2 where it is mainly applied to submerged bodies with a small propulsor unit. This approach can also be applied to aircraft or air-breathing propulsion missiles as suggested in reference 3. The boundary layer inlet concept, as applied to an airfoil, is illustrated in figure 1 [ref. 4]. The engine is shown mounted on the aft section of the wing swallowing the low incoming turbulent boundary layer momentum. Utilizing this arrangement, a beneficial trade-off between decrease in drag and increase in the fuel consumption of the engine (losses in compressor due to flow non-uniformity) is achieved.

Benefits. Recently, L. Smith [ref. 3] suggested that for aircraft propulsion, wake ingestion (low-momentum fluid intake) may be less beneficial, when compared to ship propulsion, because engines mounted on the aft section of wings only capture a small fraction of the total wetted flow over the wing. However, the application of this concept is suggested for cruise missiles because a single concentric aft-located propulsor can be used to swallow the boundary layer generated by the missile's fuselage while a bottom mounted inlet can be used to supply the core engine with distortion minimized flow. Benefits, in terms of gains in propulsive efficiency to the boundary layer intake engine, are of the order of 7-15% [refs. 3 and 5]. Recent studies [ref. 4] indicate possible reductions of 3-7% in aircraft take-off weight.

Present Utilization of Technology. No current or past production aircraft utilizes the boundary layer inlet concept. This technology has mainly been applied to torpedoes and other marine applications [ref. 3].

Configuration Integration. It is possible to extend this application to conventional aircraft by utilizing a boundary layer inlet engine mounted on the aft portion of the fuselage (to ingest the boundary layer) together with wing-mounted engines which take in distortion minimized flow. Additional applications may include the use of this technology in the Blended Wing Body aircraft concept taking advantage of the large wetted surface area of the fuselage. A major drawback of this concept is the control of separation (passively and/or actively) required in order to make the heavily distorted boundary layer flow more uniform. If flow distortion is too great, excessive loads can lead to fan blade fatigue/failure and rotating blade stall can occur.

References.

1. Wislicenus, G. F.: "Hydrodynamics and Propulsion of Submerged Bodies," *J. American Rocket Society*, Vol. 30., December 1960, pp 1140-1148.
2. Gearhart, W. S.; and Henderson, R. E.: "Selection of a Propulsor for a Submersible System," *J. Aircraft*, Vol. 3, No. 1, 1966, pp. 84-86.

3. Smith, Leroy H.: "Wake Ingestion Propulsion Benefits," *J. Propulsion and Power*, Vol. 9, No. 1, January-February 1993, pp. 74-82.
4. "Megaplanes", *Popular Science*, Vol. 246, No. 4, April 1995, p. 56.
5. Bushnell, Dennis M.: "Frontiers of the 'Responsibly Imaginable' in (Civilian) Aeronautics," 1998 AIAA Dryden Lecture.

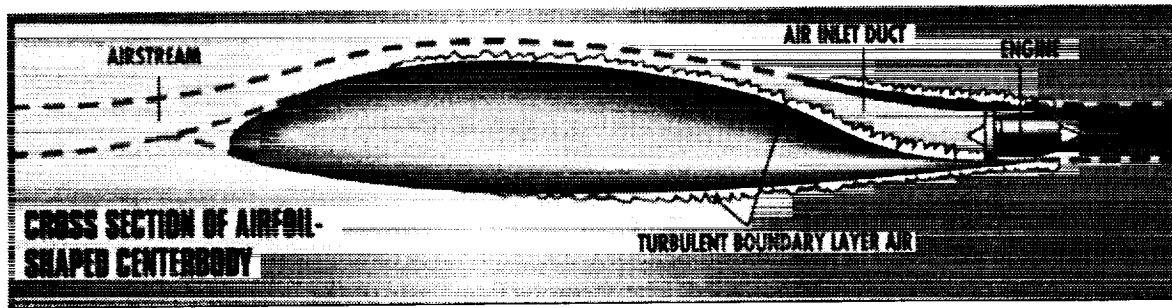


Figure 1. Boundary layer inlet concept, from ref. 5.

Laminar Flow Control

Background and Technical Description. Laminar flow control (LFC) refers to methods which artificially laminarize a boundary layer that, left to its own devices, would otherwise be turbulent. There are many reasons one may wish to have a laminar, rather than a turbulent, boundary layer. Such reasons generally involve significant reductions in skin friction and/or large reduced heat transfer rates possible with laminar (as compared to turbulent) boundary layers. Figure 1 illustrates the fundamental drag reduction potential of laminar contrasted to turbulent boundary layers as a function of Reynolds number. Because skin friction accounts for fully half of the total aircraft drag of a typical transport aircraft at cruise conditions, the appeal of laminar flow becomes obvious.

When applied to an aircraft, particularly an aircraft designed (sized) to cruise long distances, reductions in skin friction lead to significant reductions in fuel requirements. An aircraft requiring less fuel will have a lower structural and operating weight and reduced operating cost as compared to an all turbulent boundary layer aircraft carrying an equivalent payload an equal range. As will be discussed later, the basic technology exists to accomplish laminar flow control; however, uncertainty in cost and maintenance of equipment required to produce laminar boundary layers and manufacture's concerns of the risk of developing aircraft dependent on such new technology has so far prevented commercial application of LFC.

Engineers have worked since the 1930s on laminar flow control systems for aircraft. In the early 1960s Dr. Pfenninger and his team at the Northrop Company conducted full scale flight tests on the USAF sponsored X-21 experimental aircraft. Extensive regions of laminar flow up to Reynolds numbers on the order 20 to 25 million were routinely obtained by the end of the tests [ref. 1]. However, operational feasibility was not demonstrated. Because of the potential large skin friction drag reduction that can be obtained from laminar flow, research continued over the years and became particularly intense during the energy crises of the 1970s. Excellent technical and historical overviews of laminar flow control technology are contained in references 1 through 5.

Typically, LFC schemes place boundary-layer suction ports at and immediately behind the wing leading edge. This is a critical area in which to remove the low energy layers of the boundary layer due to large adverse pressure gradients that can easily amplify instabilities within the boundary layer, including crossflow disturbances that will lead to premature transition and turbulence. Cross flow disturbances become quite serious for wing sweep greater than about 20 degrees. Because most modern subsonic and supersonic cruise aircraft have swept leading edges for reasons of efficiency, the boundary layer at and near this swept edge develops a crossflow (spanwise) component to the general chordwise flow. Even after the boundary layer crossflow and other instabilities are removed, the flow will eventually become turbulent if left to its own devices. Before this occurs, another row of suction ports is introduced, and so on. Using this technique, the laminar boundary layer can be extended over a considerable chord length, perhaps in the case of a transonic aircraft to a trailing edge shock position. An experiment that proved transonic airfoils could be designed to take advantage of LFC was undertaken by NASA in the 1980s. In this experiment, the disposition and type of suction system and variation on the amount of suction was applied (parametrically) to an airfoil specially designed to promote laminar flow on the top and bottom surfaces. Reference 4 provides a summary of this experiment.

At the present time, the preferred method of controlling laminar flow at subsonic speeds is a technique called hybrid laminar flow control (HLFC). HLFC techniques place suction panels on the wing leading edge that can cover as much as the first 25 percent of the top side of the wing chord. Laminar flow is then maintained past this suction region by a favorable pressure gradient. The above mentioned transonic laminar flow airfoil experiment was modified for such a HLFC system. The experiment was very successful and the results are summarized in references 6 and 7.

NASA, Boeing, and the U. S. Air Force participated in a key flight experiment of a HLFC system on a modified Boeing 757 in the late 1980's [ref. 6]. In this experiment, a glove with a suction panel constructed of a microperforated (19 million holes) titanium surface and contoured to maximize laminar flow was mounted over a 22-foot section of the left wing of a Boeing 757. A Krueger high lift flap was integrated into the wing to serve as an insect shield during takeoff and low altitude flight. A thermal anti-ice system was also incorporated. Results showed extensive laminar flow was routinely achievable. NASA/Industry flight experiments of HLFC systems to reduce drag on engine nacelles have also shown promise. However, transonic wind tunnel tests of HLFC nacelles conducted by NASA LaRC in the mid 1990s indicated that a significant integration challenge exists to the successful implementation of HLFC nacelles on transonic transport configurations. With regard to supersonic HLFC, NASA has just completed an extensive flight experiment on a General Dynamics F-16XL aircraft. Again a section of the highly swept wing was modified with a glove designed to promote laminar flow with a microperforated leading-edge suction system to remove crossflow disturbances [refs. 8 and 9].

Results from these flight tests and experiments have been encouraging, but detailed results have been made accessible to U. S.-only sources due to the possible competitive advantage this technology may someday give American companies.

Reductions in heating rates across a laminar, compared to a turbulent, boundary layer can be particularly important for high speed aircraft where the kinetic energy of the air stream is converted to heat (as it decelerates within the boundary layer) that can significantly raise the temperature of the aircraft surface. For supersonic aircraft, the reductions in heating rates resulting from laminar flow may allow lower cost and lighter structural materials.

Studies have also shown the potential benefits of actively cooling hypersonic aircraft [ref. 10]. The cooled skin of such a vehicle may have extensive regions of laminar flow due to cool skin temperatures. Other cooling schemes for hypersonic aircraft have studied film cooling of the surface via slot injection of cool air with a laminar velocity profile.

Benefits. Commercial aircraft designs are driven by the requirements that their acquisition and operating costs allow them to make a profit for both the aircraft manufacturer and the airline companies. Profits are driven by aircraft operating costs, passenger appeal (including perceived aircraft safety issues), and any environmental factors imposed on commercial aircraft. These environmental factors can include noise regulations, possible emission reductions, and the ability to land and take off in adverse weather or congested traffic conditions. To be viable, a laminar flow control aircraft must generate greater profit than a comparable conventional (turbulent) aircraft. It could do this if it had significantly lower operating costs, including fuel usage and lower ownership costs. Obviously laminar flow technology can lower fuel usage if it reduces drag. Lower cruise drag translates into less fuel weight to carry and thus into a lighter weight aircraft which should be less expensive to manufacture. However, if the weight or cost of the laminar flow control system reverses these trends, the aircraft will become more expensive and non-competitive. Maintenance and safety issues raised by the laminar control system must also be carefully weighed. If, for example, a laminar flow aircraft is sized to complete its mission should the laminar system fail at the beginning of a trip, benefits of the system would be less than if the aircraft was sized for a failure halfway through the flight, or no failure of the laminar flow control system at all. The perception of risk can profoundly alter the design philosophy of the aircraft design and ultimately its profitability. In the following sections, a brief summary of five technical studies of the benefits of LFC applied to aircraft efficiency and operating cost are presented.

In a 1982 report [ref. 11] the Boeing Company reported on the design of a HLFC system for a Boeing 757 aircraft that laminarized 60% of the upper wing surface and 40% of the lower surface. Analysis showed it would reduce fuel consumption 8%. If the empennage was also laminarized fuel savings would increase to 12%. If the aircraft could be resized for this laminar system, there would be a further significant reduction in fuel consumption.

An unpublished study by the Mission Analysis Branch at NASA Langley Research Center [ref. 12] concluded that, with conservative assumptions, the direct operating costs of a modern long range transport aircraft would be reduced 6 percent (fuel price \$1.00/gal) if it was designed with HLFC systems. The assumptions used in this analysis included increased development costs of a billion dollars for the aircraft calculated over a 500 aircraft fleet (two percent additional flyaway costs) and an additional 5 percent airframe maintenance cost above that of conventional concepts. The aircraft was sized with sufficient reserves to complete one-half the mission in a turbulent-flow mode should the HLFC system fail in flight.

A study of the benefits of HLFC by Arcara and Bartlett is reported in reference 13 for an aircraft sized for HLFC providing 50 percent chord laminar flow for the wing upper surface and 50 percent chord for both surfaces of the horizontal and vertical tails. Results showed a 15 percent reduction in cruise fuel and a 6.5 to 10 percent reduction in DOC depending on a fuel price variation from \$0.65 to \$2.00 per gallon.

ONERA studies from 1990 are reported in reference 14 which concluded HLFC applied to a 150 and a 300 passenger long range aircraft should reduce fuel consumption nearly 15 percent. HLFC was applied to the wing, the tail and fin and the engine nacelles.

An unpublished study entitled "Potential Economic Impact of Future Large Aircraft" by the Mission Analysis Branch [ref. 15] contains results of applying HLFC to a "conventional" 800 passenger aircraft. Laminar flow was postulated to cover 60 percent of the wing upper surface, 30 percent of the lower surface, and fifty percent of the empennage surfaces. A 6.5 percent reduction in seat mile cost was calculated for typical 65 percent load factors. Fuel costs were assumed at \$0.60 per gallon.

Several studies of laminar flow applications to supersonic aircraft were sponsored by NASA as part of High Speed Civil Transport (HSCT) activity. A supersonic transport will consume more fuel per passenger mile than a conventional subsonic aircraft; thus, it might be assumed laminar flow would be particularly attractive to reduce fuel weight requirements. As an example, typical fuel fractions (fuel weight /gross weight) are on the order of 40 percent for a long range subsonic transport and can exceed 65 percent for an equivalent range supersonic transport. An additional bonus for supersonic transports is that transition Reynolds numbers are substantially higher at supersonic speeds than at subsonic speeds [ref. 8]; thus, a supersonic aircraft may require less suction than subsonic aircraft to achieve laminar flow.

The study of reference 16 by the Douglas Aircraft Company reports on a comprehensive analysis of HLFC applied to a Mach 3.2 supersonic transport. The analysis showed a distinct advantage for a full chord HLFC system as opposed to a partial chord suction system. A block fuel reduction of 14 percent and gross takeoff weight reduction of over 8 percent was obtained over a fully turbulent baseline design.

A Boeing Airplane Company study of HLFC application to a Mach 2.4 supersonic aircraft is documented in reference 17. Study results showed a block fuel reduction of 16 percent and a 12 percent reduction in gross takeoff weight.

Preliminary studies of the benefits of HLFC for supersonic aircraft was undertaken in the 1992 period and recorded in the unpublished study of reference 18. These studies sized supersonic transport concepts as a function of the amount of laminar flow assumed to cover wing, empennage and fuselage surfaces. Three cases were studied: a conventional concept with all turbulent flow; a concept resized for 30 percent laminar flow over wing/empennage surfaces and 12 percent over the fuselage; and third case with laminar flow covering 60 percent of the wing/empennage and 25 percent of the fuselage (see figure 2). Realistic weights for the suction systems were estimated from the previously mentioned Boeing and McDonnell Douglas studies. Results of the analysis showed a 9 and 16 percent reduction in gross takeoff weight and a reduction in operating cost of 8 and 10 percent for the two HLFC cases over the all turbulent vehicle.

Applications. Considering the large number of studies cited previously that showed a remarkable agreement on the advantages of laminar flow control concepts, why then has not a single commercial application of the technology been developed? The answer most likely can be traced to two factors: (1) risk and (2) the promise of larger performance gains from other more mature technologies. Both of these factors are addressed next.

(1) Risk: Current development cost for a new, large, long range subsonic transport may approach the net worth of an aircraft company. Development of a supersonic transport will undoubtedly cost much more. With such enormous sums at stake, aircraft manufacturers will not risk using technology, regardless of its promise, that has not been developed to a point that unmistakable benefits are clearly shown with real-world hardware systems in realistic airline environments. Analytical system studies have convinced most engineers that if laminar flow mechanical systems worked as well as assumed, the economic benefits are real. The experimental systems studied to date, however, consist of only small segments of the aircraft wing surface and not large complete systems that would lend confidence to building a commercial product. In previous decades, military aircraft proved new technologies often at great expense, of which the more successful ones were introduced into commercial use. In the absence of the large military programs of the past, what is needed now are large scale experimental laminar flow system technology demonstrations to reduce the risk to commercial airframe manufacturers.

(2) Alternate promising technologies: Aircraft companies are driven by the desire to increase their profits, and in large measure this is accomplished by improving the economics, safety, comfort, and environmental attractiveness of their aircraft to airlines and to the flying public (compared to a competitor's aircraft). In a sense, this pits technologies against one another as to which technology can deliver a competitive advantage at the lowest cost and the lowest risk. This can be illustrated by figure 3 from reference 18, which contains cost advantages for advances in three different technologies: laminar flow control, engine efficiency, and advanced composite construction. The advances shown are those that might reasonably be expected to be on operational aircraft in the next twenty years. Within the constraints of the study (e.g., fuel costs, aircraft configuration), it appears that larger performance gains will accrue to advances in propulsion systems and composite structures than due to laminar flow control. All things considered, engine and structure technology are thought of as more traditional, mature technologies while laminar flow control is not. For a given improvement in dollars per seat mile a manufacturer may find it more attractive to improve a more understood, less risky technology. Again the factor of risk and the level of maturity (or technical readiness) is the major issue for laminar flow control technology application. Large-scale integrated laminar-flow system demonstrations are most likely needed before airframers will consider designing laminar flow transport aircraft. Such demonstrations will have to eventually include major aircraft components such as complete wings and tail surfaces.

Looking Ahead. We can conjecture that as aircraft as we know them today become more and more efficient through conventional advances in propulsion and materials/structures technology; laminar flow control will become very attractive as one of the final remaining technologies that can deliver a large increment in performance. A more exciting scenario for the future, however, could be the advent of aircraft concepts that can take full advantage of laminar flow over major if not all aircraft surfaces, thus leading to much larger increases in performance than noted from the cases cited in this section. Perhaps the Blended Wing Body concept mentioned elsewhere in this document will lend itself to such "full coverage" laminar flow concepts. Perhaps, also, very short-chord, high-aspect-ratio wings supported by strut bracing will be able to take full advantage of laminar flow control, natural laminar flow, or a combination of the techniques. Another possibility may be that an increased environmental concern over global warming and restrictions on hydrocarbon emissions from aircraft will result in more fuel efficient aircraft designs. As noted in this paper, laminar flow control has a major impact on reducing fuel consumption and could be a major contributor to aircraft fuel efficiency.

References.

1. Wagner, R. D.; Maddalon, D. V.; Bartlett, S. W.; and Collier, Jr., F. S.: "Fifty Years of Laminar Flow Flight Testing," SAE Technical Paper 881393, October 1988.
2. Joslin, Ronald D.: "Aircraft Laminar-Flow Control," *Annual Reviews of Fluid Mechanics*, 1998, pp. 1-29.
3. Joslin, Ronald D.: "Overview of Laminar Flow Control," NASA RP-97-1407, December 1997.
4. Barnwell, R. W.; Hussanini, M.Y.: "Natural Laminar Flow and Laminar Flow Control," Springer-Verlag, ICASE/LaRC Series, 1992.
5. "Research in Natural Laminar Flow and Laminar-Flow Control," NASA CP-2487 Parts 1, 2, and 3. Proceedings of a Symposium held at Langley Research Center, Hampton, Virginia, March 16-19, 1987.
6. Harvey, W. D.; and Bobbitt, P. J.: "Toward Lower Drag with Laminar Flow Technology," Presented at the 16th Congress of the International Council of the Aeronautical Sciences, Jerusalem, Israel, August 28-September 2, 1988.
7. Bobbitt, Percy J.; Ferris, James C.; Harvey, William D.; and Goradia, Suresh H.: "Results for the Hybrid Laminar Flow Control Experiment Conducted in the NASA Langley 8-Ft. Transonic Pressure Tunnel on a 7-FT. Chord Model," NASA TM 107582, March 1992.
8. "Laminar Flow Study Predicts \$1 billion fuel saving," *Air Transport World*, November 1990, p. 8.
9. Wilhite, Alan W.; and Shaw, Robert J.: "HSCT Research Picks Up Speed," *Aerospace America*, Vol. 35, No. 8, August 1997, pp. 24-29, 41.
10. Becker, J. V.: "New Approaches to Hypersonic Aircraft," Presented at the Seventh Congress of the International Council of the Aeronautical Sciences (ICAS), Rome, Italy, Sept. 1970
11. Boeing Commercial Airplane Company: "Hybrid Laminar Flow Control Study Final Technical Report," NASA Contractor Report 165930, October 1982.
12. Memorandum to Mission Analysis Branch files, November 1990, from Head, Mission Analysis Branch, NASA Langley Research Center. Subject: Mission Analysis Branch Cost Study of Hybrid Laminar Flow Control.
13. Arcara Jr., P. C.; Bartlett, S. W.; and McCullers, L. A.: "Analysis for the Application of Hybrid Laminar Flow Control to a Long-Range Subsonic Transport," Presented at the Aerospace Technology Conference and Exposition, Long Beach, California, Sept. 23-26, 1991.
14. Thibert, J. J.; and Reneaux, V. Schmitt: "ONERA Activities on Drag Reduction," 17th ICAS Congress, Stockholm, Sweden, September 9-14, 1990, Proceedings, Vol. 1, ONERA TP No. 1990-114.
15. Small, W. J.; Morris Jr., Shelby J.; Harvey, W. Don; Martin, Glenn L.; Tice, David C.: "Economics of Advanced Subsonic and Supersonic Transports," White Paper, February 25, 1992.
16. "HSCT Concept Development Group, Advanced Commercial Programs," Douglas Aircraft Company, Long Beach, California: 1989 High-Speed Civil Transport Studies, NASA Contractor Report 4375.
17. Boeing Commercial Airplane Company: "Application of Laminar Flow Control to Supersonic Transport Configurations," NASA CR-181917, 1990.
18. Small, William J.; Morris, Jr., Shelby J.; Harvey, W. Don; Martin, Glenn, L.; Tice, David C.: Unpublished Briefing entitled "Economics of Advanced Subsonic Transports and Supersonic Transports," January 1992.

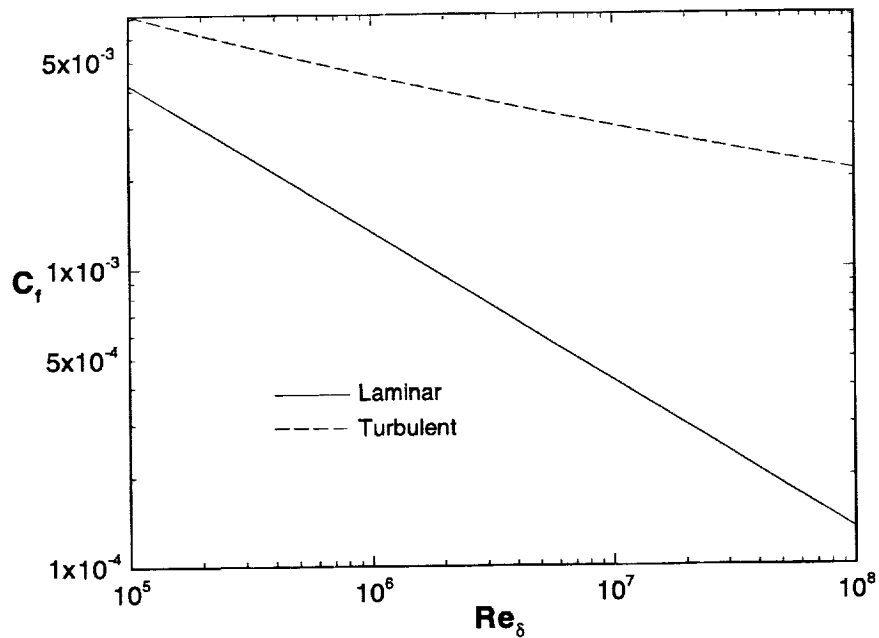


Figure 1. Effect of incompressible laminar and turbulent Reynolds Number on skin friction coefficient.

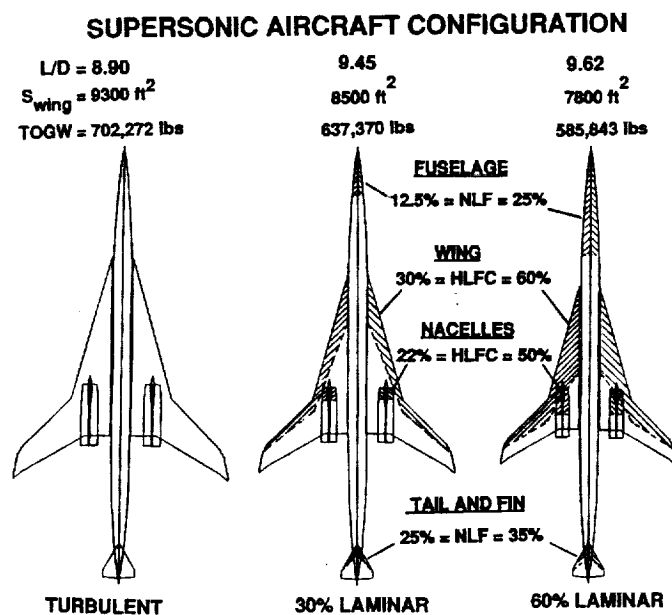


Figure 2. Parametric study of laminar flow control effects on supersonic transport sizing, from ref. 18.

7000 n.m. design range
5500 n.m. stage length
800 seats
.65 load factor

cruise Mach number = 0.85

● Baseline configuration

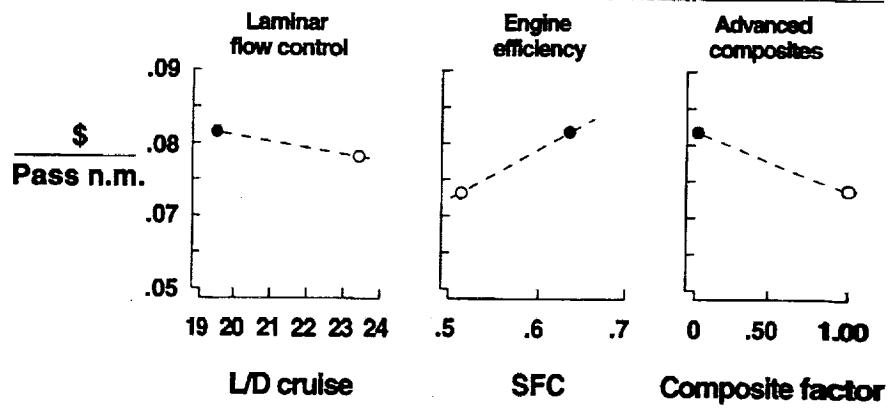


Figure 3. Sensitivity of passenger fare to advanced technology, from ref. 18.

Natural Laminar Flow

Background and Technical Description. Natural laminar flow (NLF) technology is designed to promote the advantages of laminar flow without the intercession of powered or mechanical means to extend the region of laminar flow. As discussed in the section entitled Laminar Flow Control, reasons that laminar flow is desired over an aircraft surface include reduced skin friction drag and reduced heating rates for high speed flight. Unlike the technology of laminar flow control, which has yet to find application on commercial aircraft, natural laminar flow is a technology now employed on an almost routine basis in the general aviation market. Potential benefits also are possible in the supersonic speed regime. References 1 and 2 provide a comprehensive treatment of the subject and extensive reference lists. The fairly recent successful application of NLF to general aviation aircraft was primarily the result of two factors. First, research activities have provided the understanding of the basic flow physics of laminar, transitional, and turbulent flow. This research began in the early days of NACA (mid 1930s) with studies of laminar flow airfoils as described in reference 1. A method of designing airfoil shapes to obtain desired pressure distributions was developed. This work led to the development of the NACA six-series NLF airfoils. Typically the concept that was pioneered involved tailoring the airfoil upper surface to maintain a favorable pressure gradient for as long as possible to maintain laminar flow [refs. 1-3]. Current analytical methods have extended these early ideas and allow the designer to tailor laminar airfoil design to the expected flight conditions [refs. 1 and 2]. Also, new classes of laminar flow airfoils have been extensively tested in wind tunnels and in flight [refs. 1 and 2].

The second major factor leading to the present use of NLF was the advent of very smooth metal and composite aircraft surfaces which provide the necessary smoothness to prevent disturbances causing premature transition to turbulent flow. General aviation aircraft such the Cessna Citation Jet, the Citation X, the Cirrus single engine pusher propeller light aircraft, and the Glasair single place light aircraft are just some examples of successful modern general aviation aircraft designed specifically with natural laminar flow airfoils. NLF has been applied to other specialized aircraft with short chord lengths such as gliders and modern long-duration reconnaissance aircraft. An instructive example of the methodologies employed for these low Reynolds number aircraft is contained in an informative description of the development of a low altitude RPV designed with laminar flow airfoils [ref. 4].

Although better categorized as a laminar flow control technology, other methods have been studied to determine their effect in increasing transition Reynolds number. Cooling of the boundary layer and suppression of turbulence-inducing disturbances with tailored acoustic energy [ref. 1] are two such advanced technologies which show promise.

Application of NLF concepts to large commercial subsonic and supersonic aircraft has been studied theoretically and experimentally; however, no application has entered the commercial market. An outstanding example of research directed towards large transport applications was the 757 wing noise and laminar flight tests conducted in the 1985 time period [ref. 1 and 2]. This experiment involved placing a fiberglass/foam core glove over a section of a 757 wing adjacent to and outboard of the left nacelle. This glove had somewhat less sweep than the 757 wing. Test results indicated that NLF could be maintained to between 20 and 30 percent chord over the top surface of the glove. Noise from a pylon mounted engine was found to have a minimal impact and then only on the lower surface of the glove. Means for protecting the surface against insects was also found to be important since laminar flow coverage was reduced when the test glove was not protected from insect contamination during takeoff and low-altitude operation. The dominant cause of transition, when it occurred, was believed to be cross-flow disturbances.

Besides requiring careful design of the airfoil and close attention to surface smoothness, laminar flow wings must minimize cross-flow contamination. Crossflow disturbances cause premature transition and, to minimize this effect (for natural laminar flow airfoils), necessitate wings with low-sweep

leading edges. Cross-flow disturbances become quite serious at angles of wing leading edge sweep greater than about 20 degrees. Figure 1 from reference 5 illustrates this point. On this figure a semiempirical curve is drawn at the approximate boundary between regions where NLF and Laminar Flow Control (LFC) are appropriate with current day technologies. Transition Reynolds numbers quickly decrease as wing sweep angles become larger than about 20 degrees. Almost no laminar flow can be expected at sweep angles above 50 to 60 degrees unless laminar flow control methods are employed.

Boundary layer transition Reynolds number has been found to increase with increasing supersonic Mach numbers [refs. 2, 6]. The fact that achieving laminar flow might be easier at supersonic speeds than at subsonic speeds has important implications for the use of both laminar flow and laminar flow control technology for supersonic aircraft. Applications of laminar flow technology to supersonic cruise aircraft can have a greater impact on performance than on subsonic aircraft. Refer to the Laminar Flow Control section in this document for more discussion on this point. An innovative theoretical application of natural laminar flow to a supersonic transport is described in reference 7. This study looked at a supersonic transport concept designed with a nouter cranked wing sweep of only 20 degrees instead of the typically moderately-swept (approximately 45 degrees) outboard wing sections of supersonic transport concepts. Chord Reynolds numbers appear low enough on this outer wing panel to support large regions of natural laminar flow.

Benefits. As mentioned in the previous section, general aviation aircraft are now using laminar flow airfoils for wing surfaces. Drag reductions up to 24 percent are claimed for business jet aircraft incorporating natural laminar flow over wings, fuselage, engine pods, and empennages [ref. 1 and 2]. For general aviation aircraft (especially business aircraft) speed is as important as efficiency. Laminar flow aircraft are thus capable of cruising at higher airspeeds for a fixed throttle setting than comparable turbulent designs.

Commuter aircraft with their moderate chord Reynolds numbers may be candidates for natural laminar flow technology. Reference 8 describes a study by ONERA and Aerospatiale for a short-haul commuter jet aircraft. Study results indicated a 10 percent drag reduction would be possible at cruise conditions through application of laminar flow. Current thinking is that large commercial transonic transport aircraft will rely on laminar flow control to achieve substantial benefits.

The study of reference 7 describes a supersonic transport concept that would develop laminar flow over an unswept outer panel wing. Depending on the extent of laminar flow achieved over the outboard wing, gross takeoff weight savings of over 10 percent are expected. This is a very significant savings, and can be appreciated by realizing that the entire payload weight of a supersonic transport is on the order of 6 percent. Figure 2 from reference 7 shows the weight reduction benefits of NLF. Subsequent studies by the Lockheed Aeronautical Systems Co. [ref. 9] have also looked at the possibilities of increasing the extent of supersonic laminar flow over outer wing panels of a supersonic transport and have concluded that significant gains in aircraft performance are possible.

Innovative studies by Gibson and Gerhardt [ref. 10] have looked at the possibilities of achieving laminar flow over the surface of a supersonic transport by actively cooling an entire (unswept) wing surface. Although the obvious integration problems of this cooled concept into a realistic supersonic transport configuration have yet to be resolved, the concept nonetheless remains attractive.

References.

1. Barnwell, R. W.; Hussanini, M. Y.: "Natural Laminar Flow and Laminar Flow Control," Springer-Verlag, ICASE/LaRC Series, 1992.
2. "Research in Natural Laminar Flow and Laminar-Flow Control," Proceedings of a Symposium held at Langley Research Center, Hampton, Virginia, March 16-19, 1987.

3. Harvey, W. D.; and Bobbitt, P. J.: "Toward Lower Drag with Laminar Flow Technology," ICAS-88-4.1.2. Presented at the 16th Congress of the International Council of the Aeronautical Sciences, Jerusalem, Israel, August 28- September 2, 1988.
4. Siddiqui, Shahid; and Kwa, Teck-Seng: "The Design and Flight Testing of a Long Endurance RPV," 17th ICAS Congress, Stockholm, Sweden, September 9-14, 1990, Proceedings, Vol. 2, ONERA TP No. 1990-11.
5. Harvey, W. Don; Forman, Brent: "Future Regional Aircraft Market Constraints, and Technology Stimuli," NASA TM 107669, 1992.
6. Jullie, Don W.; and Hopkins, Edward J.: "Effects of Mach Number, Leading-Edge Bluntness, and Sweep on Boundary-Layer Transition on a Flat Plate," NASA TND-1071, September 1961.
7. Fuhrmann, Henri D.: "Application of Natural Laminar Flow to a Supersonic Transport Concept," AIAA 93-3467, August, 1993.
8. Thibert, J. J.; and Reneaux, V. Schmitt: "ONERA Activities on Drag Reduction," 17th ICAS Congress, Stockholm, Sweden, September 9-14, 1990, Proceedings, Vol. 1, ONERA TP No. 1990-114
9. Harcrow, Aaron: "Part Span Natural Laminar Flow," Lockheed Aeronautical Systems Company; NASA contract NAS1-19348, Task 12, Oct 1994.
10. Gibson, Berry T.; and Gerhardt, Heinz A.: "Development of an Innovative Natural Laminar Flow Wing Concept for High Speed Civil Transports," Presented at the AIAA Applied Aerodynamic Conference , Aug. 9-11,1993, Monterey, CA.

Effect of Sweep on Transition for Wind Tunnel and Flight Experiments

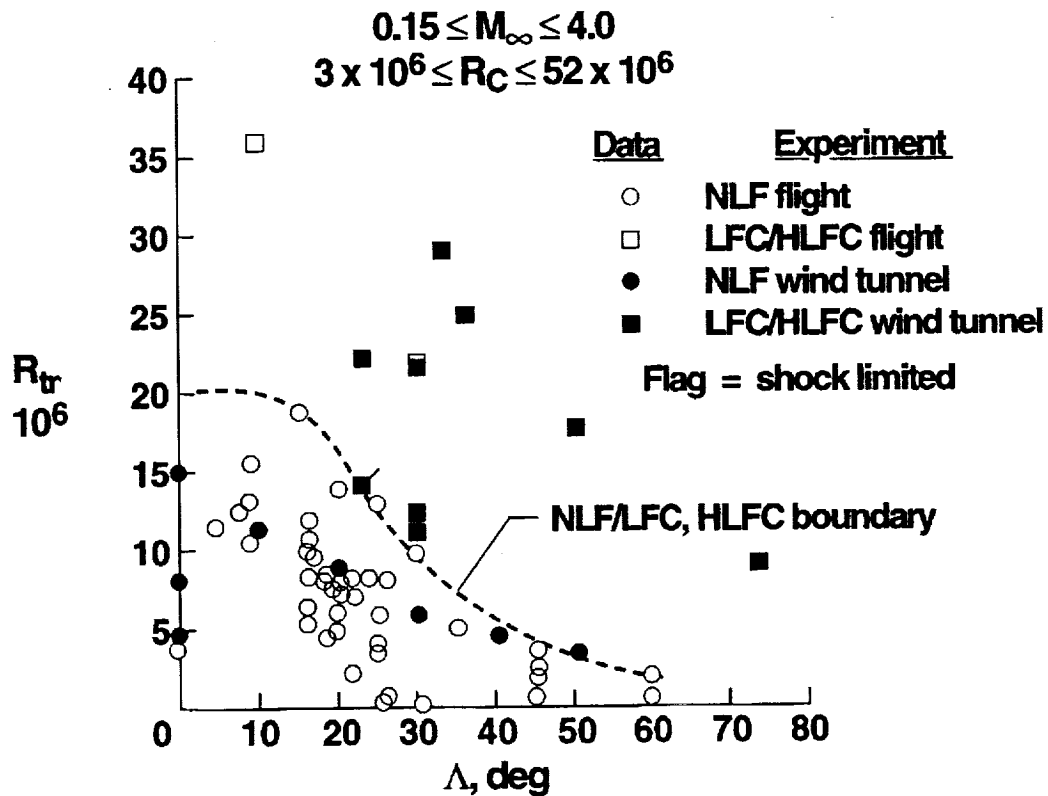
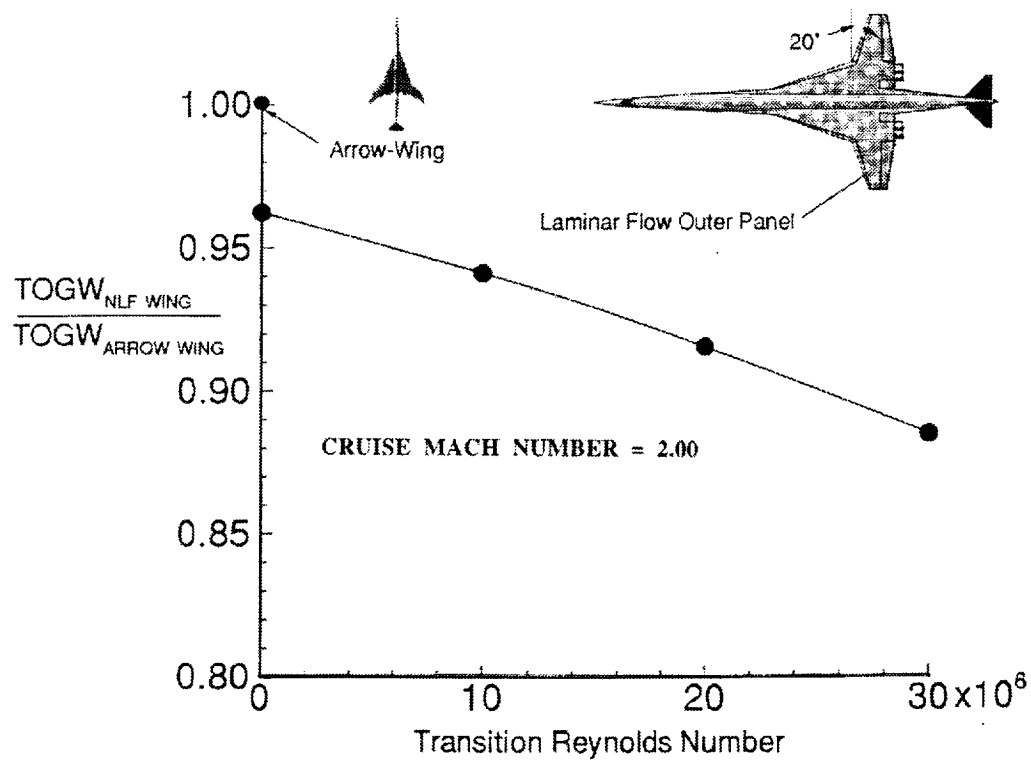


Figure 1. Effect of wing sweep on transition, from ref. 5.



Supersonic Natural Laminar Flow HSCT Concept

Figure 2. Takeoff weight reduction with natural laminar flow over outboard wing panels, from ref. 7.

Favorable Shock/Propulsive Surface Interferences and Interactions for Supersonic and Hypersonic Concepts

The open literature cites at least three different applications for the favorable use of shock waves to provide aeropropulsive performance benefits for supersonic and hypersonic concepts. The first two involve the tailoring of the external shape of vehicles to produce a beneficial shock wave when the vehicle is exceeding the speed of sound. The last one is a specialized application of localized supersonic flow for improved engine efficiency. Details of the three applications follow.

Supersonic Wing/Nacelle Integration and Favorable Aerodynamic Interference for Supersonic Airplane Design.

As far back as 1935, favorable interference was being addressed as a means of drag reduction. Busemann [ref. 1] theoretically described the judicious use of interfering flowfields to noticeably reduce wave drag due to thickness for two-dimensional wings. The idea, known as the Busemann biplane (see figure 1), was to establish a pattern in which the shock waves created at the leading edge of each wing are cancelled at the shoulders of the opposite wing where flow expansion occurs. For this set of wings, a symmetrical pressure distribution is produced, and the wave drag is zero. This is true only at the design Mach number; only partial cancellation occurs at off-design conditions. This concept was theoretically extended to three-dimensional systems by Ferri and Clarke [ref. 2].

The proper design and placement of propulsion nacelles and the design of the airframe were found to be mutually beneficial in three different ways. First, they can provide improved cruise aerodynamic efficiency. Second, the interference effects from the nacelle on the airframe can be made favorable. Lastly, the interference effects of the airframe flow structure can provide favorable effects on the flow going into the inlet of the propulsion system.

A report authored by Kulfan [ref. 3] addressed a variety of ways to achieve favorable aerodynamic interference for supersonic aircraft design. He concluded that a parasol wing concept had the greatest potential benefits for a small supersonic aircraft. The parasol wing concept is actually a three-dimensional application of the Busemann biplane wing cancellation concept, in which the forebody compression pressures are reflected off the wing onto the back of the body. This cancels part of the body wave drag and enhances the overall aerodynamic efficiency of the vehicle. The aerodynamic characteristics of the parasol wing are shown in figure 2. They include a favorable interference lift force and a partial wave drag cancellation on the body (which produces a thrusting force). A sketch of a body parasol-wing configuration is shown in figure 3. If a similar approach is taken with nacelles instead of a body, a double-parasol wing vehicle can be created (see figure 4). The planform shape of the wing is created to allow for the maximum nacelle interference lift per unit wing area. Analytical results (figure 5) for a Mach 3 small supersonic military aircraft showed that, when compared to a conventional aircraft with a reference flat wing design, the double-parasol wing vehicle has a 25% improvement in cruise L/D. When the nacelle area growth is optimized for the parasol wing, the potential L/D improvement increases to 37%. In fact, up to a 20% improvement in cruise L/D can still be achieved using a parasol wing over a conventional aircraft with an optimized wing designed for the cruise speed.

For the parasol wing concept, it is assumed that the inlets of the nacelles are still in the freestream part of the flow. Pritulo, et al. [ref. 4] addressed the benefits of locating the inlets inside of the airframe-altered flowfield. A sketch of the nacelle placement is shown in figure 6. They were able to show that proper inlet placement can improve the L/D at Mach 4 by 7% at AOA=8 degrees and up to 24% at AOA=0 degrees (figure 7). Furthermore, the ability to precompress the flow going into the inlets allows for higher values of mass capture than if they were in undisturbed flow. This actually allows the designer two choices: either accept the improved capability in the aircraft or reduce the size of the inlet capture area to make the engines more efficient.

Work at the University of Maryland [ref. 5] has developed a new class of waveriders that use predetermined flowfields from the leading edge of the vehicle (using an osculating-cone inverse design technique) to create a pre-compressed, uniform flow for capture by the engine inlets. While the aerodynamic performance of the new waveriders is similar to conical flow-derived waveriders, they possess advantages in inlet inflow properties that vary by less than one percent (see figure 8) and good volumetric efficiency. The inverse-design approach taken by the University of Maryland has been applied to a large class of supersonic and hypersonic Mach number forebody designs that maintain good aerodynamic performance and flow uniformity at off-design Mach numbers.

An historical application of this technology is the XB-70, which exploited favorable aerodynamic interference in its design. The reason why these types of systems have not been utilized in other aircraft designs is primarily because, aside from the HSCT, there are few aircraft designed for supersonic cruise efficiency. Furthermore, some of the designs pose a structural challenge because they do not contain long straight structural members. However, advances in materials may reduce the necessity for long, straight, structural members.

Each concept described above shows aerodynamic performance benefits over traditional design approaches, making them more cost effective. From an environmental standpoint, there is the potential that less fuel (and less exhaust) would be required because a precompressed inlet flow would require smaller engines for the same amount of thrust. Furthermore, some of the favorable aerodynamic interference may actually reduce noise signatures at cruise because of wave cancellation.

The integration of these concepts into configuration design requires that a rigorous approach be taken in the external shaping of wings, bodies, and nacelles. Off-design trades would have to be accomplished to ensure that performance is not significantly affected when not travelling at the design Mach number.

Thrust Deflection for Hypersonic Cruise.

In 1967, Krase published a note concerning the use of thrust deflection for hypersonic airbreathing vehicles [ref. 6]. By theoretically combining aerodynamic and propulsion parameters, the purpose of the note was to show that, with the moderate L/D ratios of hypersonic cruise vehicles and the low gross-thrust/ram-drag ratios of scramjet engines, there may be a substantial benefit to thrust deflection. A critical point is that the gross thrust (which can be much larger than the net thrust in an airbreather) is the part that is deflected. The deflected thrust can be used for decreasing wing size and weight at a constant altitude or to increase the cruise altitude of a prescribed configuration. For the latter, there would be an associated increase in capture area to maintain the air mass flow entering the engine. The analysis shows that for a vehicle with an L/D of 4 and a gross-thrust/ram-drag ratio of 1.1, a 14 deg., thrust deflection would provide a 34% greater range and fly 15,000 ft. higher than a vehicle without thrust deflection. It would also require a 52% larger capture area. The benefits are also evident at conditions corresponding to supersonic transport cruise conditions (L/D of about 8 and gross-thrust/ram-drag ratio of approximately 1.2), where a 7.1 deg. thrust deflection would provide about 4% greater range. At present, the topics of trim, stability, and control have not been addressed with respect to this type of thrust deflection.

There are a number of reasons why this concept has not been utilized. Most notably, there are very few research programs addressing supersonic and hypersonic cruise configurations. Second, the engines would be heavier because of the additional capture area required. This additional weight is countered by a reduction in the aerothermal loads on the vehicle and engine because of the higher cruise altitude.

As previously mentioned, there would be a tremendous range increase in the case of a hypersonic vehicle with thrust deflection.

Incorporation of this concept into vehicle design would involve either including the thrust deflection angle in the nozzle design or allowing for actuation of internal (and external) nozzle surfaces to allow for variable thrust deflection. This, of course, adds complexity and weight to the vehicle.

Shock Wave Engine.

Although this is purely an engine-only concept, the use of localized supersonic flow allows it to be discussed herein. The shock wave engine [ref. 7] is considered an unsteady flow device which uses a separate wave rotor along with the low and high pressure turbines to create a localized region of supersonic flow. The shock waves that are produced cause pressure ratio increases that are 2 to 10 times greater than pressures in a system using a conventional precompressor. An added benefit of the shock wave engine is considerable weight reduction based on two factors. First, shock compression takes place in significantly shorter distances than for steady flow compression, so size is reduced. Second, the compression pressure ratio across a single shock is much greater than in a steady flow diffuser for the same change in subsonic velocities.

There are no known configurations that currently use the shock wave engine. There have been problems in the past with fabrication of the wave rotor portion and the survivability of that portion at high rotation rates. However, Weber in reference 7 states, "... with careful design of the seals, the wave engine can greatly exceed the efficiency and be considerably lighter and more compact than conventional turbines or reciprocating internal combustion engines." This is a technology that is not quite ready for application today, but may be ready in 10-20 years with further research and development.

References.

1. Busemann, Adolf: *Atti del V. Convegno "Volta."* Rome, Reale Accademia d'Italia, 1935.
2. Ferri, Antonio; and Clarke, Joseph H.: "On the Use of Interfering Flow Fields for the Reduction of Drag at Supersonic Speeds," *J. of Aero. Sci.*, Vol. 24, No. 1, January 1957, pp. 1-18.
3. Kulfan, Robert M.: "Application of Favorable Aerodynamic Interference to Supersonic Airplane Design," SAE 901988, October 1, 1990.
4. Pritulo, T. M.; Gubanov, A. A.; and Voevodenko, N. V.: "Favorable Interference of Optimized Wing-Body Combination with Inlets at Supersonic Speed," AIAA 95-3946, September 1995.
5. Takashima, Naruhisa; and Lewis, Mark J.: "Waverider Configurations Based on Non-axisymmetric Flow Fields for Engine-Airframe Integration," AIAA 94-0380, January 1994.
6. Krase, W. H.: "Thrust Deflection for Cruise," *J. Aircraft*, Vol. 4, No. 2, March-April 1967, pp. 162-164.
7. Weber, Helmut E.: *Shock Wave Engine Design.* Wiley Interscience, 1994.

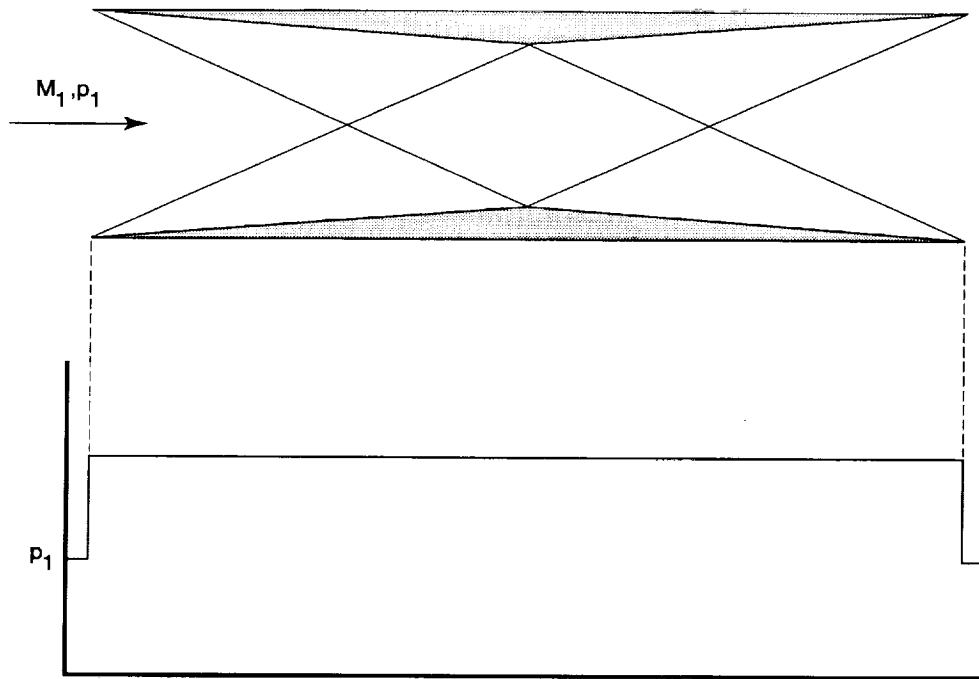


Figure 1. Busemann biplane concept with theoretical pressure distribution on an inside surface of the wing, from ref. 1.

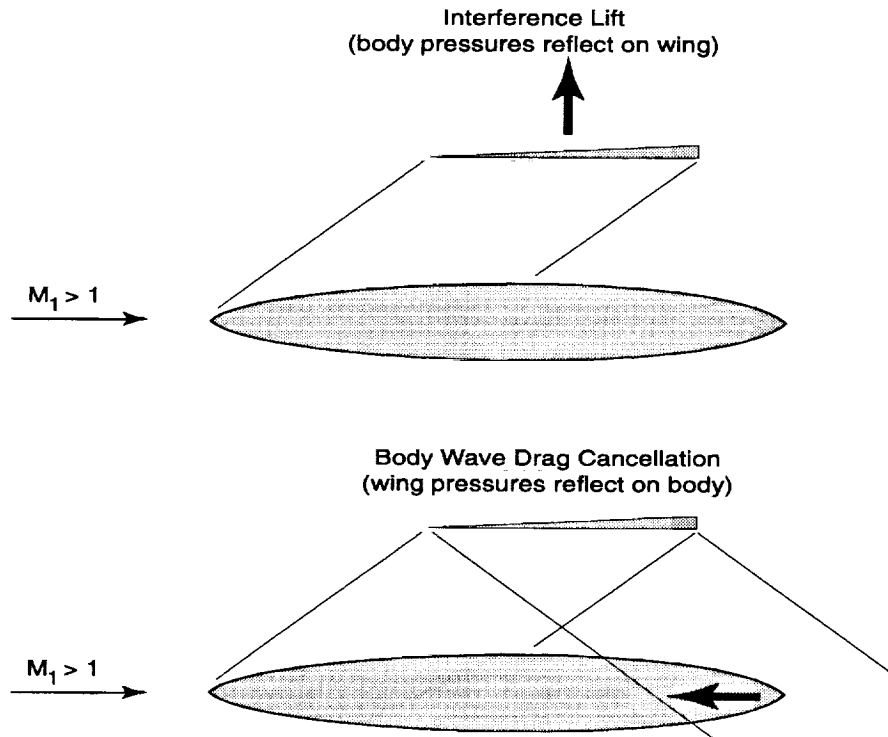


Figure 2. Parasol wing aerodynamic features, from ref. 3.

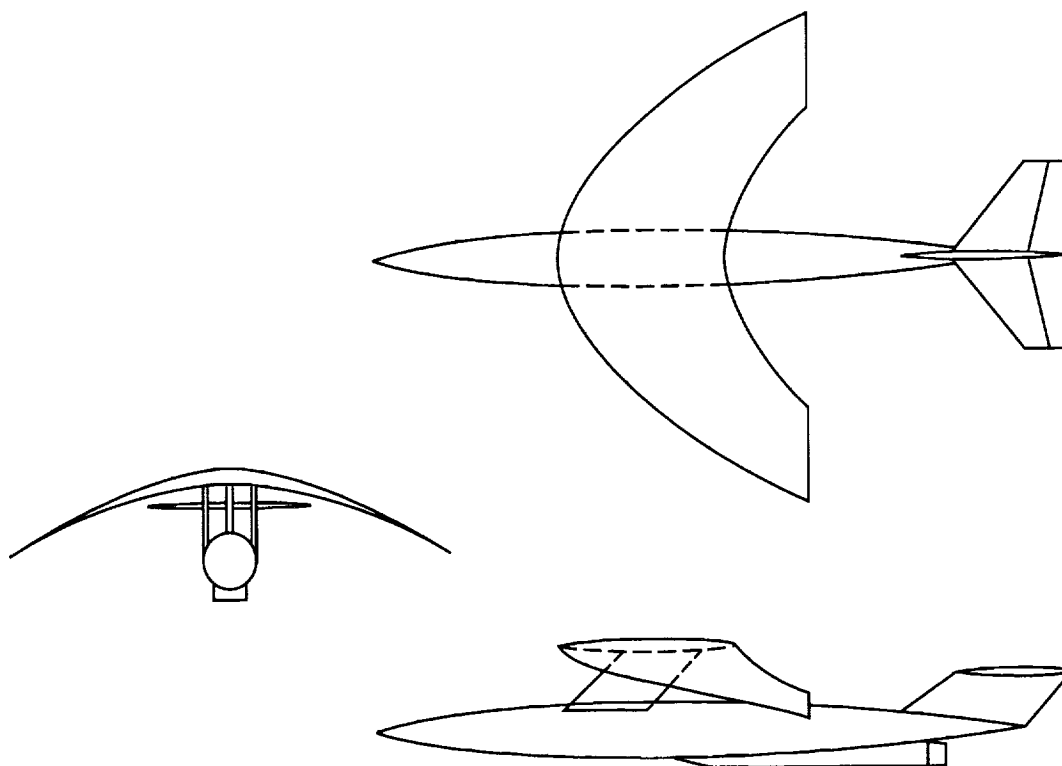


Figure 3. Body parasol-wing configuration features, from ref. 3.

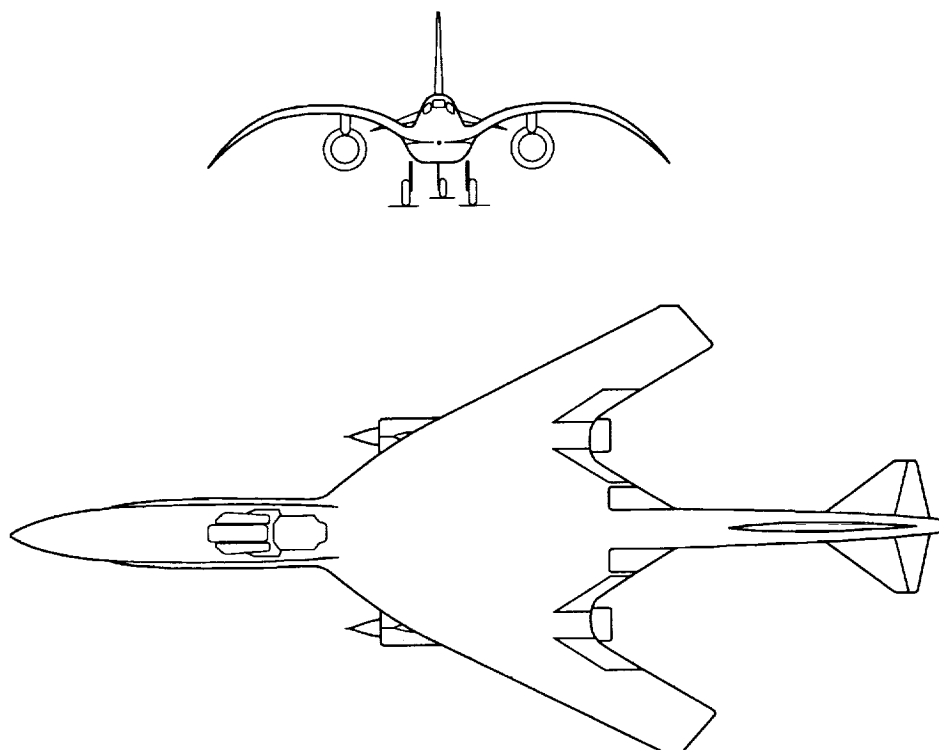


Figure 4. Double-parasol wing configuration definition, from ref. 3.

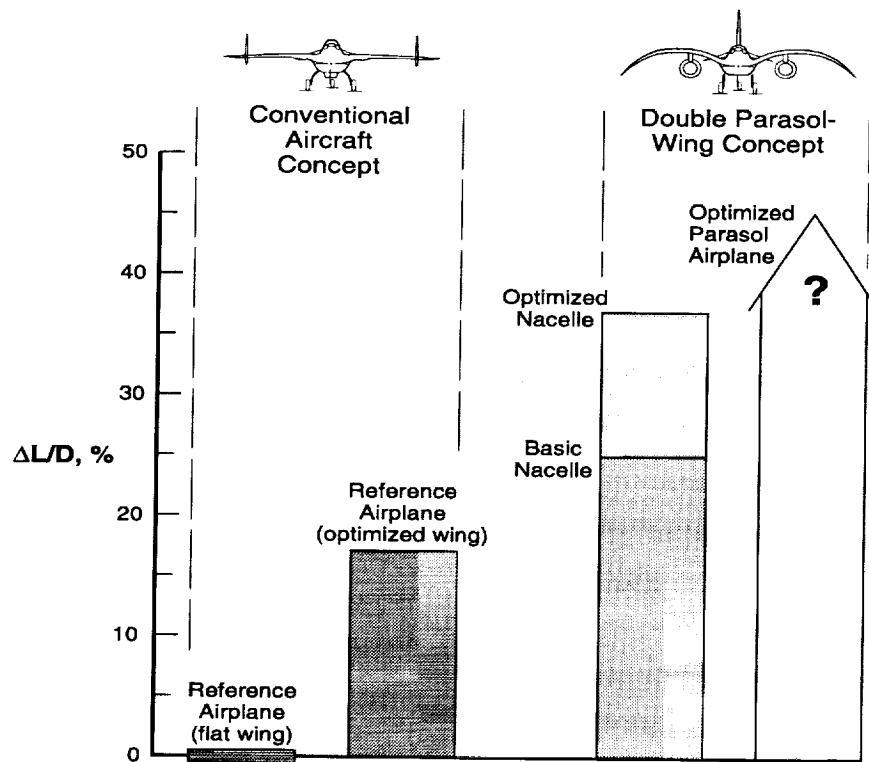


Figure 5. Improvement in maximum L/D improvement for a Mach 3.0 Double-Parasol Wing Configuration, from ref. 3.

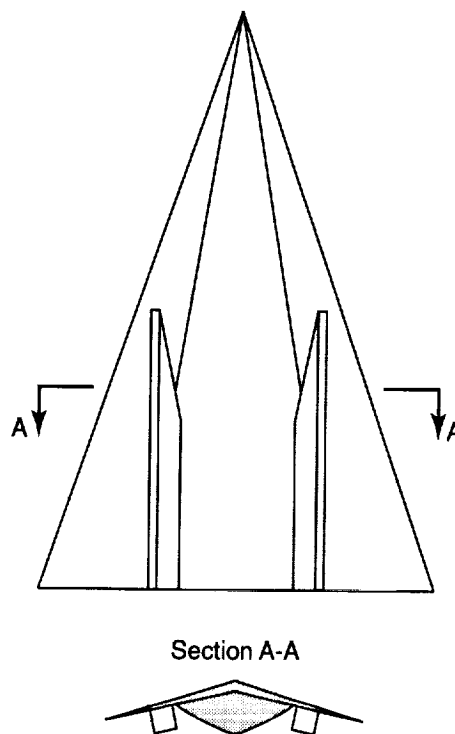


Figure 6. Airframe-Inlet configuration of Pritulo, et al., from ref. 4.

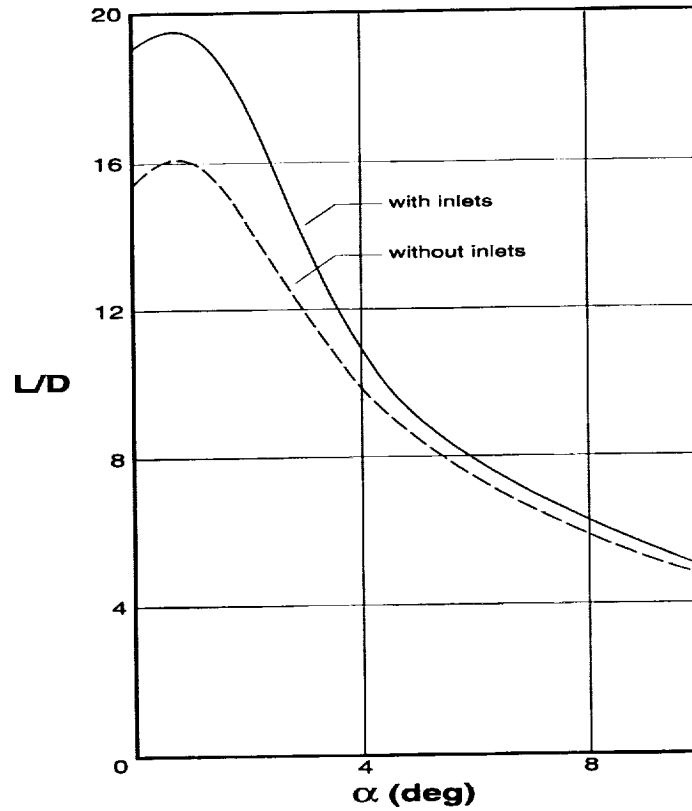


Figure 7. Favorable aerodynamic improvement from airframe-inlet interference, from ref. 4.

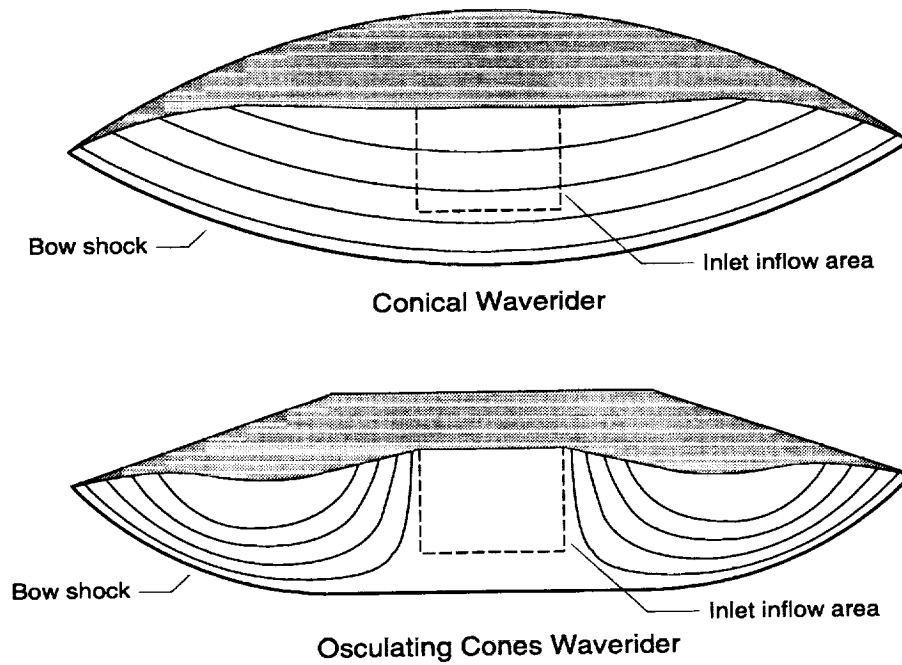


Figure 8. Pressure contours at the exit plane of two Mach 6 wave riders designed with conical and osculating cones methods, from ref. 5. (Typical inlet inflow area added for this report.)

Other Technologies

Thrust Vectoring

Technical Description. Thrust vectoring is exactly what its name implies; the thrust generated by an engine is turned (vectored) by the engine's nozzle to create a force that is used to provide braking, lift, and/or control authority for an aircraft or missile. This technology has been investigated in various forms since the 1950s, mainly for use on military aircraft. The two basic methods used to accomplish the vectoring, mechanically actuated flaps in the exhaust flow and fluidic flow turning, are shown in Figures 1 and 2, respectively. Refer to reference 1 for a summary of aircraft thrust vectoring schemes. Thrust reversal for braking is the only widely used form of thrust vectoring in service to date; however, note that while thrust vectoring nozzles can provide both vectoring and reversing, thrust reversers as used in transport aircraft are not generally vectoring nozzles but dedicated thrust reverser systems. Also note that some High-Speed Civil Transport (HSCT) studies examined tilting nacelles for providing a lifting vector during cruise, but this survey will not address those studies.

Mechanical or fluidic thrust vectoring can be used to provide pitch vectoring, yaw vectoring, or a combination of the two (multi-axis vectoring). Nozzle design defines which of these functions are available for any given installation. Most of the following text describes mechanical thrust vectoring, which can be accomplished by several means. Little open literature describing fluidic thrust vectoring is available, and only a limited description of this technology is included below. In supersonic flow, fluidic nozzles have limited turning capability (less than 30° , so far), although in subsonic flow, fluidic thrust reversers may be possible (i.e., reversing fan flow). Only mechanical nozzles can be used to provide thrust reversal of engine core flow or direct lift (for short/vertical takeoff and landing), and both require turning supersonic flow 90° or more.

The most common use of mechanical thrust vectoring is thrust reversal. Jet transports have used this technology for decades to safely reduce landing rollout distances with something other than heavy, expensive and maintenance intensive wheel-mounted brakes. Thrust reverser systems add a margin of safety in terms of reduced stopping distances and increased directional control during landing rolls and rejected takeoffs on contaminated runways (e.g., water, snow, and/or ice). Flow is turned 135° or more (from directly aft to forward) to provide braking power for the aircraft. Various mechanisms are used to effect the flow turning including clamshell (e.g., Boeing 737-100, see Figure 3) and cascade (Figure 4) reverser designs. Both designs physically block some or all of the engine core and/or fan flow. On a clamshell reverser, the blocked flow (efflux) is turned and vectored forward and concentrated into two large jets by the clamshell doors. This efflux must be oriented to avoid impingement on the aircraft, exhaust gas re-ingestion, foreign object damage (F.O.D.), and fuselage buoyancy effects, as well as to create a downforce. Cascade reversers operate in a different manner. Doors normal to the exhaust flow are used as blockers to the flow inside the nacelle (fan flow). Portions of the nacelle slide forward or aft to provide a flow exit and expose grid-like cascade vanes that direct the diverted flow. This type of reverser can distribute vectored flow more precisely than other reverser designs. Other thrust reversal techniques have been proposed to turn the fan flow of high-bypass ratio turbofans, including fabric parachutes deployed from the cowl of a pylon-mounted jet engine and blockerless reversers that use diverter jets (a fluidic technology) instead of blocker doors in a cascade-type reverser.

Thrust reversal as defined in the previous paragraph is almost exclusively used on the ground. In fact, reverser lockout systems are employed to ensure that the reversers are not inadvertently deployed in flight. Enormous forces can be generated by in-flight thrust reverser deployment, possibly causing loss of control and/or structural damage; however, some aircraft with cascade reversers are designed to use reverse thrust for emergency descents at idle thrust settings. The military fighter/attack aircraft community likes the idea well enough to consider using thrust reversing nozzles on future tactical aircraft. In this case, nozzles used for thrust vectoring functions would be modified to allow for thrust

reversal as well. The aircraft would then have ground braking capabilities that would reduce field length requirements and an increase in airborne agility allowed by almost instantaneous airborne braking followed by acceleration, since thrust is used for both.

Pitch, yaw, and multi-axis vectoring nozzles are more complex than thrust reversers. Flow must be turned smoothly and efficiently to provide the proper thrust vector required for any given flight condition without significant thrust loss. Generally, nozzles with only pitch vectoring authority are rectangular in shape and have one or more flaps oriented parallel to the pitch-yaw plane of the aircraft. These nozzles are often called 2-D (i.e., two-dimensional) because they use planar plates to divert flow. These nozzles can accommodate thrust reversal requirements as well, either by splitting a single vane and hinging it about its trailing edge to block flow or by pinching off the flow using multiple vanes (Figure 5). Other pitch-vectoring nozzle designs include various gimbaling nozzles and the single expansion ramp nozzle (SERN).

The British Aerospace/McDonnell Douglas AV-8B Harrier family of aircraft (and their predecessors, the P1127 and the XV-6A Kestrel, circa 1959 and later) uses a special kind of pitch vectoring nozzle found only on their Rolls Royce Pegasus engine (Figure 6). The nozzle is an elbow that rotates on a bearing fitted to the engine case. Two nozzles ahead of the aircraft center of gravity use fan air for thrust, while two nozzles aft of the aircraft center of gravity use jet exhaust for thrust. The nozzles can rotate about 100° (from directly aft to slightly forward of down). The nozzles create lift for vertical takeoff and landing when pointed down or thrust for forward flight when pointed aft. If pointed all the way forward, braking force (and lift) is created. Note that the Pegasus engine only vectors thrust through the aircraft center of gravity; therefore, the engine is used to control lift and thrust, not attitude. The four nozzles (port front and rear, starboard front and rear) provide a stable lifting force for the aircraft, and the rotation capability allows transition from vertical to horizontal flight and vice versa.

Most research has neglected yaw-only vectoring, perhaps because pitch control adds little mechanical complexity once yaw is introduced (for some nozzle configurations) or perhaps because yaw-only has fewer benefits than other forms of thrust vectoring. Note that some yaw-vectoring flight experiments have been performed on the Grumman F-14 for one-engine-out control, and nozzles with yaw only (or yaw plus reverse) could be designed in the same fashion as 2-D pitch-only nozzles.

Several nozzle designs are suitable for multi-axis thrust vectoring (i.e., combinations of pitch plus yaw or pitch plus yaw plus reverse). One type uses multiple paddles to divert flow (Figure 7). The paddles are hinged at their base and can be activated singly or in concert with each other to provide the required thrust vector. This type of nozzle has been used on research aircraft to investigate the basics of thrust vectoring under flight conditions. It is inefficient both from the vectoring and nozzle efficiency points of view and the paddles are heavy, but paddle nozzles are cheap, easy to model, and can be retrofitted to existing airframes albeit with significant weight penalties (e.g., F-18 HARV, Figure 8). Another type of multi-axis vectoring nozzle is the axisymmetric (round) design. An axisymmetric nozzle looks like and is only slightly more mechanically complex than a supersonic convergent/divergent nozzle. Both use metal petals driven by hydraulic actuators to optimize the shape of the nozzle for various flight conditions; however, the multi-axis thrust vectoring (MATV, Figure 9) nozzle can make changes besides nozzle exit area. The nozzle vectors thrust by shortening the actuators on one portion of the nozzle and lengthening them on the diametrically opposite portion, driving the nozzle exit out of plane. Since the nozzle is round, the deflection can be in any direction; therefore, the effective vectoring volume is a cone. The extent of the cone is fixed by the amount of petal overlap required to create a functional nozzle and the travel of the actuators. Axisymmetric nozzles are attractive for retrofit to existing aircraft, but they are much more difficult to integrate into the airframe than 2-D nozzles and have higher signatures. Other more complex designs can be used for multiaxis thrust vectoring such as the clamshell nozzle [ref. 1].

Fluidic thrust vectoring (FTV) turns the exhaust of an engine using the influence of a secondary fluid stream. The concept is theoretically intriguing; however, creating an FTV system that can provide vectoring sufficient for control at an economical engine bleed rate is very challenging. The challenge becomes more severe as Mach number increases (i.e., for the same bleed rate, vectoring angle decreases with Mach number). For these reasons, FTV may be practically limited to use as an aircraft trim device. Several techniques can be used to effect FTV. Shock-vector control (see Figure 2) injects a sheet of secondary air into the primary exhaust stream from a slot in the divergent flap of a convergent-divergent nozzle. The secondary flow effectively creates an obstruction to the primary exhaust, resulting in an oblique shock across the primary flow. As the supersonic primary flow crosses the oblique shock, it is vectored away from the slotted divergent flap. Varying the mass flow rate of the injected sheet controls the vectoring angle, and thrust vectoring levels adequate for transitory control ($>15^\circ$) have been achieved in static tests of this technique. Since the vectoring is achieved by creating a shock across the primary flow, moderate thrust losses are incurred. Other fluidic concepts include passive cavity designs that turn the flow by influencing boundary layer separation characteristics, synthetic jets that turn the flow without any net injected mass flow, devices that use the Coanda effect to turn the flow as it leaves the nozzle, and counterflow thrust vectoring designs that inject flow upstream into the primary exhaust (again creating an oblique shock, but with less secondary mass flow). Fluidic methods can be used in similar ways to control nozzle throat area for engine throttling and flow expansion for off-design thrust performance gains.

Benefits/Liabilities. Thrust vectoring provides agility, controllability, performance, and survivability benefits. Agility and controllability are particularly enhanced at low airspeeds and/or high angles of attack where aerodynamic control surfaces are least effective, thereby expanding the flight envelope. Performance is improved by reducing the size of aerodynamic control surfaces (or eliminating some entirely), since drag and weight for these surfaces decrease with size. Thrust vectoring is most efficient at low vectoring angles; therefore, trim drag reductions are easily achieved. Control surfaces are programmed for minimum drag instead of aircraft trim, and thrust vectoring can provide the required trimming forces. Survivability is enhanced by increased low airspeed control, since recovery from (or avoidance of) departure from controlled flight is easier. In addition, reduced control surface size can result in reduced aircraft signature if desired.

Thrust vectoring also increases design freedom. Tailless aircraft (Figure 10), direct side force control designs, and vertical takeoff and landing aircraft, among other concepts, become practical. Even more mundane aircraft could benefit from the application of thrust vectoring. Personal (roadable) aircraft, conventional passenger and cargo transports, and unconventional transports like the Blended-Wing-Body could be improved by the addition of thrust vectoring.

The additional weight required for implementation and increased nozzle complexity are the major liabilities of mechanical thrust vectoring systems. Some nozzle designs are detrimental to aircraft signature (aural, infrared, and/or radar). If thrust vectoring replaces conventional aerodynamic controls, some of the high-speed operating envelope can be lost unless the engine is oversized. Overall aircraft system life cycle costs could also increase on thrust-vectoring aircraft, depending on the aircraft platform. Detailed systems analyses must be performed to make that determination.

Specific benefits are listed below:

Agility and Controllability Benefits

- Enhanced Low Airspeed Agility and Controllability

- Expanded Envelope (Post-Stall Maneuvering Capability)

- Higher Instantaneous Turn Rates

- Improved Fuselage Aiming

Performance Benefits

- Reduced Takeoff Roll

- Reduced Trim Drag

- Reduced Control Surface Size (Weight and Drag Reductions)

- Design Optimization (e.g., Supersonic Wing Design, Tail Volume Coefficients)

Safety/Survivability Benefits

- Recovery from Deep Stall or Departure

- Aerodynamic Control Surface Backup

- Reduced Control Surface Size (Signature Reduction)

In addition to the benefits noted above, fluidic thrust vectoring holds promise of further improvements. Nozzle weight could actually decrease with an FTV system. Actuators and their structural supports are not required, and nozzle cooling requirements are reduced. Survivability is further enhanced by FTV due to its inherent signature benefits. Moving nozzle geometry and the associated multitude of gaps and edges are eliminated, and the fixed geometry of an FTV nozzle allows nozzle shaping freedom. In addition, life cycle cost savings could be realized. Parts count is drastically reduced from the typical mechanical nozzle (vectoring or not), and the entire FTV system is inherently less complex, reducing acquisition and maintenance costs. If other mechanical nozzle functions (e.g., throat area control and expansion control) are incorporated into the FTV nozzle, the benefits are magnified. On the other hand, note that some FTV nozzles (e.g., shock-induced turning) may increase nozzle noise.

Present Utilization of Technology. Pitch, yaw, and multi-axis vectoring nozzles are not currently in service on any commercial aircraft, although most jet transports use thrust reverser systems. As previously noted, the Harrier series of aircraft and some Eastern Eurasian attack aircraft use vectored thrust for V/STOL. Tactical military aircraft fitted with pitch-vectoring nozzles will begin entering service around the turn of the century (e.g., Su-37, F-22A). Note that the first pre-production F-22A Raptor (using 2-D pitch vectoring) flew on September 7, 1997. The Joint Strike Fighter (JSF) may utilize pitch plus yaw or pitch plus yaw plus reverse nozzles, and the vertical/short takeoff versions of the JSF will require at least pitch vectoring nozzles. The only other aircraft using these types of nozzles today are research and prototype aircraft (e.g., F-18 HARV, X-31, F-15 ACTIVE, YF-22, Su-37 prototype). Substantial increases in engine thrust-to-weight ratios (T/W) due to research in the Integrated High Performance Turbine Engine Technology (IHPTET) initiative will eventually result in higher T/W vehicles, making thrust vectoring much more attractive.

Configuration Integration. Center of gravity (cg) location with respect to nozzle location is critical on a thrust-vectoring aircraft. For example, if the nozzle is used for control, there must be a sufficient moment arm between the nozzle and the cg to let the vectoring provide control forces without unduly over-sizing the engine(s). Load paths must exist around the nozzle to transfer the forces generated by vectoring to the remainder of the airframe. In addition, nearby structure must not intrude into the vectoring volume produced by the nozzle. In other words, booms, tails, etc. must not be in the exhaust at any possible deflection angle. Note that the Su-37 can only utilize pitch vectoring (as currently configured), because yaw vectoring could damage the rearward-facing radar between its nozzles. The purpose of thrust vectoring integration on any given airframe must also be considered. Using vectoring for trim imposes completely different requirements than using vectoring for post-stall control or vertical takeoff and landing.

References.

1. Berrier, B. L., and Re, R. J., A Review of Thrust-Vectoring Schemes for Fighter Aircraft, AIAA Paper 78-1023, July, 1978.
2. Wing, David J.: "Fluidic Nozzle Technology," Presentation to the Langley Aeronautics Technical Committee, August 20, 1996.
3. Berrier, Bobby: "Propulsion Airframe Integration Technology, Reflections, Babbling, Introspection, Rambling, Thoughts, Musing, Meandering, Ruminations, and Other Possibly Related War-Stories," Presentation to the Langley Aeronautics Technical Committee, August 12, 1996.
4. Minton, David H.: *Boeing 737*, Aero Series No. 37, Tab Books, Blue Ridge Summit, PA, 1990, p. 22.
5. United Technologies Corporation: "The Aircraft Gas Turbine Engine and Its Operation," Pratt & Whitney Operating Instruction No. 200, 1988.
6. Mangold, P.; and Wedekind, G.: "Inflight Thrust Vectoring, a Further Degree of Freedom in the Aerodynamic/Flightmechanical Design of Modern Fighter Aircraft," AGARD Conference Paper 90N28528, April, 1990.
7. Taylor, John W. R. (editor), *Jane's All the World's Aircraft, 1988-89*, Jane's Information Group Limited, Surrey, UK, 1988, p. 714.
8. Markman, Steve; and Holder, Bill: *One-of-a-Kind Research Aircraft*, Schiffer Publishing Ltd., Atglen, PA, 1995, p. 12.

Bibliography.

- Snow, Barton H.: "Thrust Vectoring Control Concepts and Issues," SAE Conference Paper 901848, 1990.
- Herrick, Paul W.: "Relationships Between Thrust Vectoring/Reversing Fighter Effectiveness and Air-to-Air Missile Technology," SAE Conference Paper 901845, 1990.
- Yetter, Jeffrey A.; Asbury, Scott C.; Larkin, Michael J.; and Chilukuri, Krish: "Static Performance of Several Novel Thrust Reverser Concepts for Subsonic Transport Applications," AIAA 96-2649, 1996.
- Herbst, Dr. W.-B.: "Thrust Vectoring - Why and How?," ISABE Paper 87-7061, 1987.
- Geidel, H. A.: "Improved Agility for Modern Fighter Aircraft, Part II: Thrust Vectoring Engine Nozzles," ISABE Paper 87-7062, 1987.
- Asbury, Scott C.; and Capone, Francis J.: "Multiaxis Thrust-Vectoring Characteristics of a Model Representative of the F-18 High-Alpha Research Vehicle at Angles of Attack from 0° to 70° ," NASA TP-3531, December 1995.
- Re, Richard J.; and Carson, George T., Jr.: "Static Internal Performance of Ventral and Rear Nozzle Concepts for Short Take-off and Vertical-Landing Aircraft," NASA TP-3103, September 1991.
- Asbury, Scott C.; Gunther, Christopher L.; and Hunter, Craig A.: "A Passive Cavity Concept for Improving the Off-Design Performance of Fixed Geometry Exhaust Nozzles," AIAA 96-2541, July 1996.
- White, S.N.: "Feasibility Study for Integrating Thrust Vectoring as a Primary Flight Control System," NASA CR-165758, Rockwell International Corporation, 1981.
- Dorsett, Kenneth M.; and Mehl, David R. (LMTAS): "Innovative Control Effectors (ICE)," Final Report for September 1994 - January 1996, Wright Labs TR-96-3043, January 1996.
- Roetman, E. L.; Northcraft, S. A.; and Dawdy, J. R. (BDSG): "Innovative Control Effectors (ICE)," Final Report for October 1994 - January 1996, Wright Labs TR-96-3074, March 1996.
- Krase, W. H., "Thrust Deflection for Cruise," *J. Aircraft*, Vol. 4, No. 2, March-April 1967, pp. 162-164.
- Coe, Paul L., Jr.; McLemore, H. Clyde; and Shivers, James P.: "Effects of Upper-Surface Blowing and Thrust Vectoring on Low-Speed Aerodynamic Characteristics of a Large-Scale Supersonic Transport Model," NASA TM X-72792, November 1975.
- Tape, R. F.; Glidewell, R. J.; and Berndt, D. E.: "STOL Characteristics of a Tactical Aircraft with Thrust Vectoring Nozzles," AIAA 87-1835, June 1987.
- Petit, John E.; and Scholey, Michael B.: "Analysis, Design and Test of Thrust Reverser and Thrust Vectoring Systems for STOL Transport Aircraft," AIAA 73-1218, November 1973.
- Petit, John E.; et al.: "Thrust Reverser and Thrust Vectoring Literature Review," AFAPL-TR-72-4, April 1972.

Archom, Tanda L.: "Performance Comparison of Dual and Single Flow Thrust Vector Nozzles," California Polytechnic Institute Presentation, September 18, 1996.

Carpenter, Dr. Thomas W.: "Cal Poly Thrust Vectoring Research," California Polytechnic Institute Presentation, September 18, 1996.

Stephenson, Frank: "Jet Set (Interview with Dr. Anjaneyulu Krothapalli)," Florida State University, retrieved on August 7, 1996.

From the Internet.

NASA Photos: <http://nsl.larc.nasa.gov>

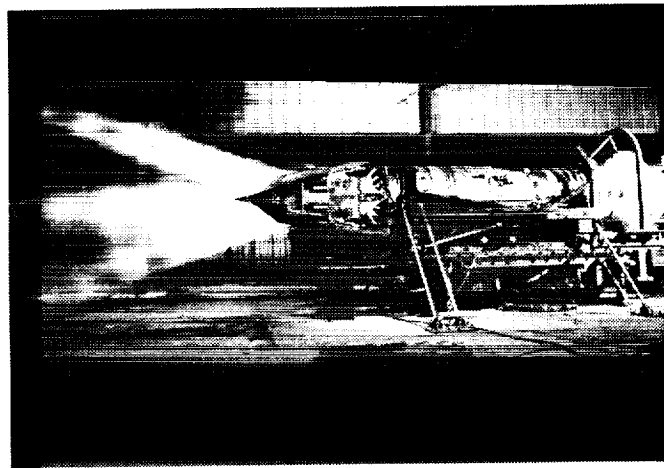


Figure 1. Time-lapse photo of Pratt & Whitney F119 in test stand showing pitch vectoring (P & W Photo).

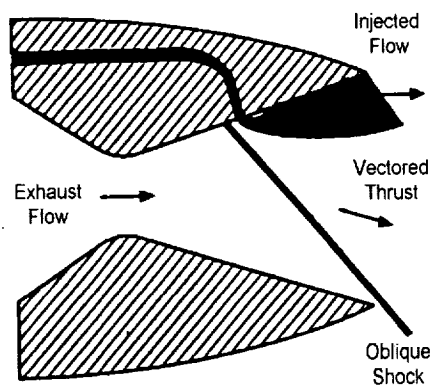


Figure 2. Shock vector control, a.k.a., shock-induced turning, from refs. 2 and 3.

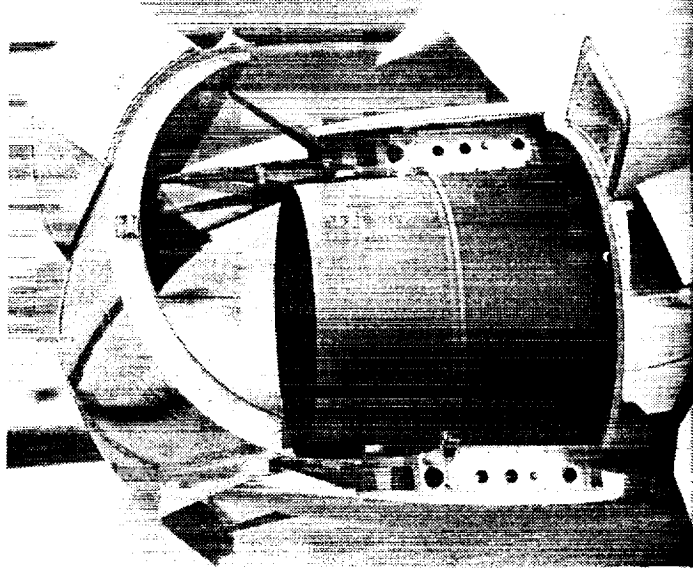


Figure 3. Clamshell thrust reverser on Boeing 737 (Boeing photo from ref. 4).

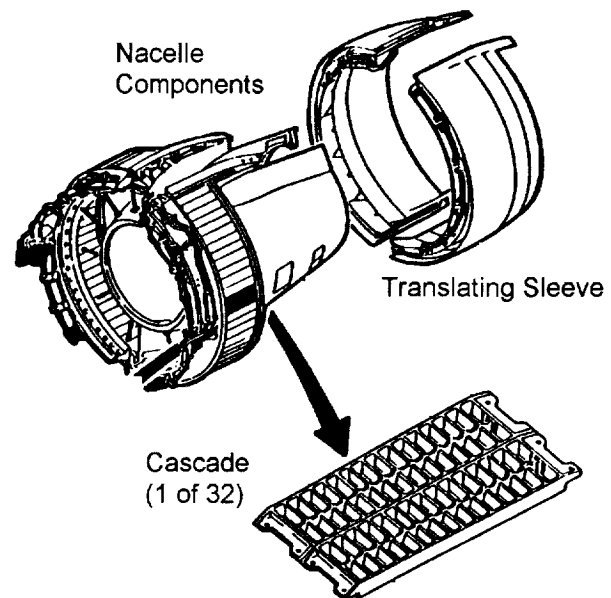


Figure 4. Cascade thrust reverser components, from ref. 5.

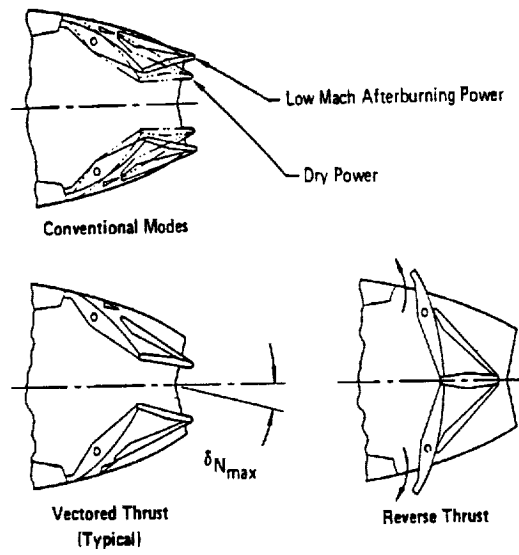


Figure 5. Pitch plus reverse thrust vectoring nozzle vane geometry, from ref. 6.

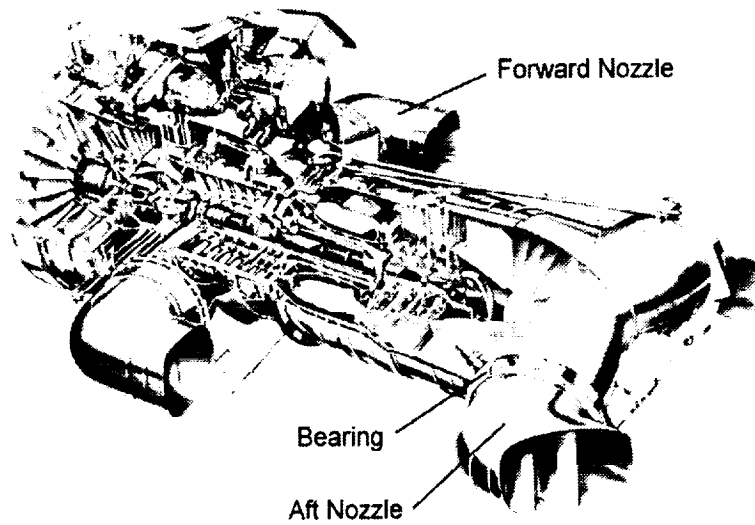


Figure 6: Rolls-Royce Pegasus 11-21 turbofan, from ref. 7.

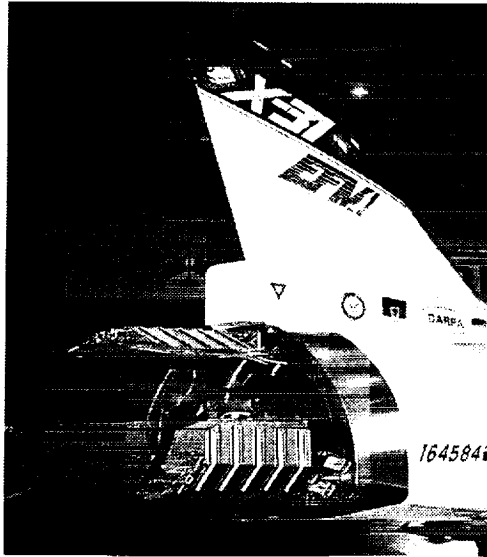


Figure 7. Multi-paddle thrust vectoring nozzle on X-31 (NASA photo).



Figure 8. F-18 High-Alpha Research Vehicle (HARV) on test stand (NASA photo). (Note vectored thrust with respect to engine axis.)



Figure 9. F-16 Multi-Axis Thrust Vectoring (MATV) demonstrator with axisymmetric thrust vectoring nozzle. (USAF photo from ref. 8.)

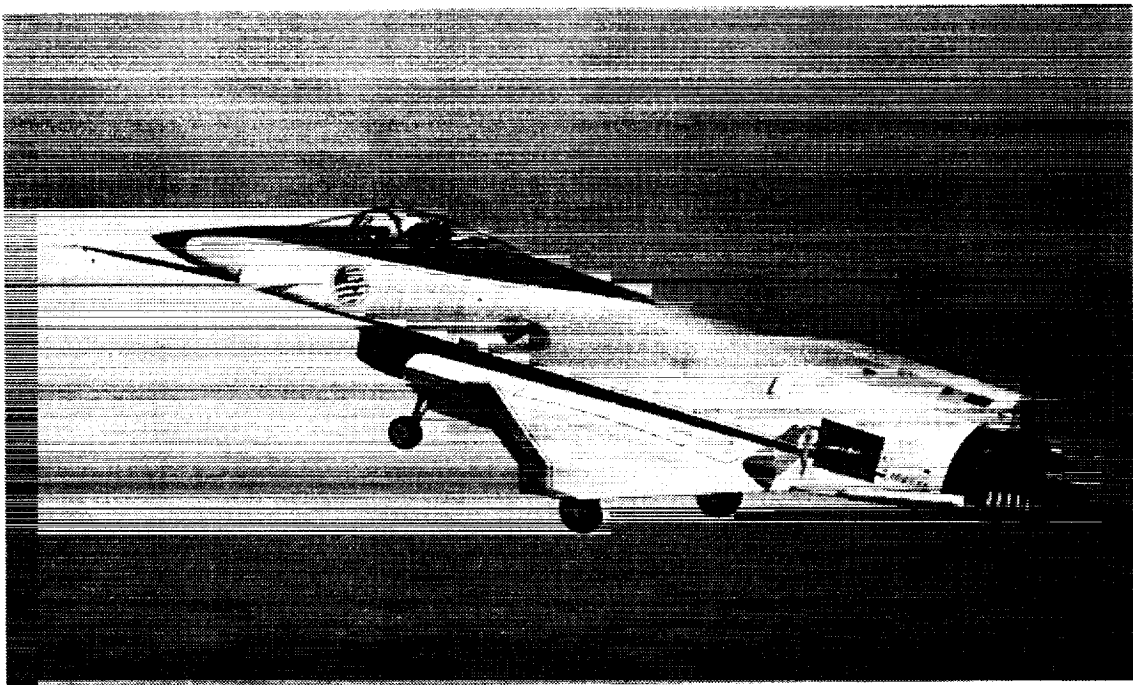


Figure 10. Artist's concept of quasi-tailless X-31 (NASA photo).

Pneumatic Vortex Control

Background and Technical Description. Pneumatic vortex control is the technology of using high energy blowing air or suction to increase high-lift capability of aircraft and to also increase maneuver control of these aircraft. Several quite different concepts such as spanwise blowing for wing leading edges and control surfaces and fluid strake concepts have been developed to take advantage of this technique and are illustrated in figure 1 and described below in the following sections.

Leading Edge Spanwise Blowing: As the angle of attack of an aircraft wing or control surface such as a canard or horizontal tail is increased, several flow phenomena may occur [ref. 1]. A wing with a moderate leading-edge sweep of approximately 40 degrees will generally develop an attached leading edge flow that, as the angle of attack is increased, will accelerate to higher velocities and increase lift. At some angle of attack the upper surface high velocity (low pressures) cannot be sustained and the upper surface airflow separates and the wing begins to lose lift (stalls). For wings of higher leading-edge sweeps on the order of 60 degrees or greater, as the angle of attack is increased, a stable leading edge vortex begins to form on the wing upper surface behind the leading edge. This vortex consists of a tightly wound energetic tornado-like structure that effectively energizes the boundary layer and prevents the wing upper surface airflow from separating. At very high angles of attack the vortex will burst, beginning at the wing trailing edge and progressively moving forward towards the wing apex as angle of attack is increased. This will decrease lift and usually generates nose-up pitching moments.

Wing planforms designed with wing sweeps between 40 and 60 degrees lie in a region that generally realizes a leading edge vortex at lower angles of attack and a stall-like separation at higher angles of attack. It is in this region of sweep angles (40 to 60 degrees), particularly for fighter aircraft, that spanwise blowing (pneumatic) concepts have been devised to prolong the leading edge vortex and increase the usable angle of attack and controllable lift range of aircraft. Typically high energy air is directed transversely over the wing from a port located on the fuselage side slightly above the wing surface. The most common scheme positions the jet just aft and parallel to the wing leading edge as shown in figures 1a and b. A variation on this scheme distributes a portion of the air jets to outer wing panels so as to increase the wing span exposed to high energy air jets as shown in figure 1c [ref. 2]. Other variations on the theme have looked at pulsating jets as a means of reducing jet mass flow and increasing effectiveness.

Trailing Edge Spanwise Blowing: Spanwise blowing has also been studied to control the separation that can occur over trailing edge flaps at high lift conditions [refs. 3 and 4]. In this type of blowing scheme, a jet of high velocity air is directed transversely parallel to and behind the wing trailing edge flap hinge line (see fig. 1b). It has been shown that this air jet can substantially delay the onset of flow separation over the flap, thus increasing usable lift of the wing-flap system.

Fluid Strake: Another application of blowing has been developed that augments the lift of fighter type wings with a jet sheet formed by blowing from a series of small in-line holes located in the side of the fuselage ahead of the wing. The fluid strake is illustrated schematically in figure 1d and acts in a manner similar to a fixed physical strake to generate a stable vortex flow over the wing surface downstream of the blowing jets [ref. 5].

Forebody Yaw Control: Related to fluid strake is the forebody control concept (fig. 1e) that consists of round or slotted jet exits located near the aircraft nose and when used differentially provide useful yaw control at high angles of attack in the regime where vertical tails lose effectiveness [refs. 6-9]. Reference 8 reports on nose jet control experiments on a full scale F/A-18 in the NASA Ames Research Center National Full-Scale Aerodynamics Complex. Pneumatic nose jets for yaw control are similar in principal to the F-18 HARV articulated nose-strake experiments, in which small hinged nose strakes were asymmetrically deployed for yaw control at high angles of attack [ref. 10].

The foregoing discussions are vastly simplified since the mechanism of stall and vortex formation is a function of many factors including leading edge design (sharp leading edges at one extreme), leading and trailing edge control surfaces and boundary layer control devices such as vortex generators. Detailed information may be obtained from the extensive literature on the subject.

Benefits and Applications. Leading edge spanwise blowing has been investigated on wind tunnel models of various complexity and on a full scale F4C fighter aircraft. Wind tunnel models have represented F4, F-5F, YF-17, F/A-18, and generic models with wing sweeps up to 60 degrees. The full scale F4C experiments were conducted by McDonnell Douglas Corporation under contract to the U.S. Air Force. This aircraft was modified to incorporate a leading edge jet at the 13 percent chord location and a jet blowing over the trailing edge flap jet at the 88 percent chord location. A limited series of flight experiments ended in September 1979. Apparently results with the spanwise blowing system showed it was as effective as the standard boundary layer control system on the aircraft. NASA was interested in modifying this aircraft to determine if improvements could be made by placing additional spanwise blowing ports on the outboard panel of the wing. Although flight experiments were never carried out on a full-scale aircraft, a series of experimental wind tunnel tests investigated the effects of this distributed blowing system (fig. 1c). In general it was concluded the most favorable effects of spanwise blowing on the high-angle-of-attack dynamic lateral-directional stability and control characteristics were achieved with all blowing inboard [ref. 11]. All blowing outboard appeared to produce a maximum lift at a lower angle of attack than inboard blowing [ref. 12], and this can have a beneficial effect for Navy aircraft requiring good over the nose pilot view angles for carrier landings. Overall it did not appear from these tests on an F4C model that major improvements could be gained from the distributed blowing concept over and beyond the all inboard system.

Observations. Pneumatic blowing has received extensive attention from researchers; however, despite the large amount of research, these systems have not been incorporated on any operational aircraft up to this time. The most likely reason is that no clear cut advantages of pneumatic blowing has emerged to date when all the advantages (higher lift, greater control) are weighed against the disadvantages (loss of engine thrust due to compressor bleed, cost, complexity, and safety). Overall aircraft integration trades can be expected to lead designers towards less complex, lighter weight solutions for operational aircraft. The time may come however, when unique aircraft requirements, such as STOL, aggressive missile evasion maneuvers, signature issues, and size constraints may yet provide pneumatic vortex controls an opportunity to pay their way onto new aircraft designs.

References.

1. Campbell, James F.: "Augmentation of Vortex Lift by Spanwise Blowing," *J. Aircraft*, Vol. 14, No. 9, September 1976, pp. 727-732.
2. Huffman, J. K.; Hahne, D. E.; and Johnson Jr., T.D.: "Experimental Investigation of the Aerodynamic Effects of Distributed Spanwise Blowing on a Fighter Configuration," Presented at the AIAA 2nd Applied Aerodynamics Conference, August 21-23, 1984.
3. Dixon, C.J.: "Lift and Control Augmentation by Spanwise Blowing Over Trailing-Edge Flaps and Control Surfaces," AIAA 72-781, August 1972.
4. Dixon, C. J.; Dansb, Ted; and Poisson-Quinton, Philippe: "Benefits of Spanwise Blowing at Transonic Speeds," Presented at the XI ICAS Conference, Portugal, September 1978.
5. Zeigler, H.; Wooler, P. T.: "Aerodynamic Characteristics of a Jet Sheet Vortex Generator," NASA Contractor Report 158904, June 1978.
6. Nguyen, L. T.; and Gilbert, W. P.: "Impact of Emerging Technologies on Future Combat Aircraft Agility," AIAA 90-1304, May 1990.
7. Lamar, John E.: "High Angle of Attack Aerodynamics," A Lecture in the AGARD Special Course Edition Entitled: Engineering Methods in Aerodynamic Analysis and Design of Aircraft, May 1991.

8. Lanser, Wendy R.; Meyn, Larry A.: "Forebody Flow Control on a Full Scale F/A-18 Aircraft," *J. Aircraft*, Vol. 3, No. 6, November-December 1994, pp. 1365-1371.
9. Brandon, Jay M.; Simon, James S.; Owens, D Bruce; and Kiddy, Jason S.: "Free-Flight Investigation of Forebody Blowing for Stability and Control," AIAA 96-3444, July 1996.
10. Murri, Daniel G.; Shah, Gautam H.; DiCarlo, Daniel J.; and Trilling, Todd W.: "Actuated Forebody Strake Controls for the F-18 High-Alpha Research Vehicle," *J. Aircraft*, Vol. 32, No. 3, May-June 1995, pp. 555-562.
11. Hahne, David E.: "Free-Flight Wind-Tunnel Investigation of Effects of Spanwise Blowing on the Dynamic Lateral-Directional Stability and Control Characteristics of a 0.13-Scale Model of a Swept-Wing Fighter," NASA TP 2492, Oct. 1985.
12. Huffman, J. K.; and Hahne, D. E.; and Johnson Jr., T. D.: "Experimental Investigation of the Aerodynamic Effects of Distributed Spanwise Blowing on a Fighter Configuration," AIAA-84-2195, presented at the AIAA 2nd Applied Aerodynamics Conference, Aug. 21-23, 1984, Seattle, WA.

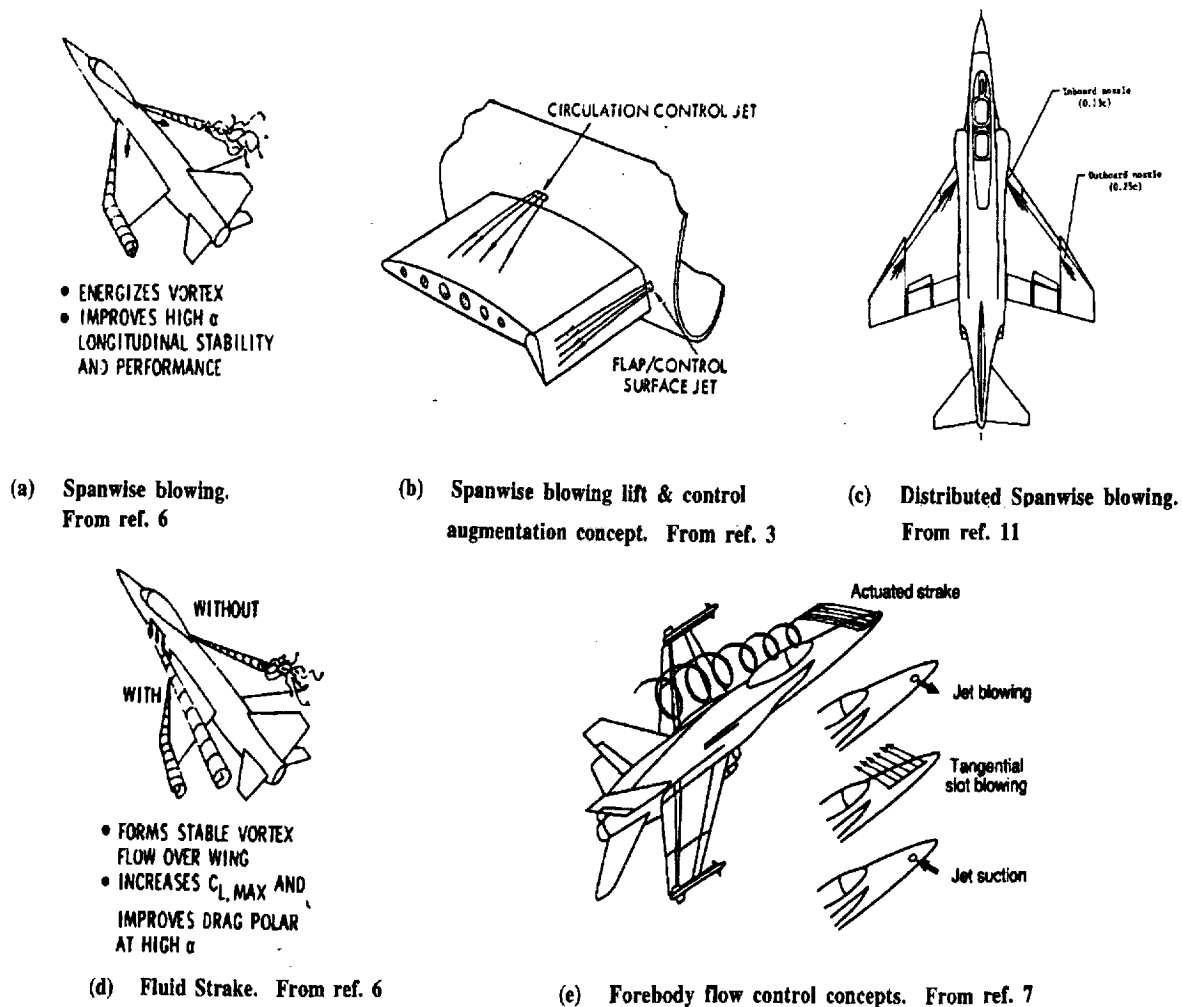


Figure 1. Pneumatic vortex control concepts.

Evolutionary Vehicle Concepts Utilizing SnAPII Technologies

Introduction

The technologies reviewed in Part I of this paper have all been tested and evaluated, at least to some extent, over the past eighty years. The historical data begs the question: based upon the possible performance increases these technologies offer, why haven't they been incorporated into modern aircraft designs? We suggest two reasons: perceived technical risk and, more importantly, the performance benefits of the individual technologies do not universally cover their life cycle costs.

Frequently, the design and life cycle costs of adding one technology are fundamentally similar to the cost of adding another different, yet potentially synergistic, technology. Therefore, the potential performance (and other) benefits of using several SnAPII technologies in synergy may outweigh the individual costs because the benefits are additive while the costs not not be. This section of the paper will illustrate the potential benefits of this design philosophy using both existing SnAPII technologies and existing aircraft design configurations.

The approach used was to conceptually retrofit an existing aircraft design (i.e., with a new wing, removal of the tails, change in engine integration, etc.) with alternate components incorporating SnAPII technologies. Two baseline aircraft types were selected: a current-technology, long-range conventional widebody aircraft (LRWB) and a current-technology, aluminum construction Blended Wing Body aircraft (BWB) [Ref. 1]. Conceptual models of these designs are shown in Figures 1 and 2 with design performance parameters shown in Table 1. Note that both designs have long range design missions, therefore their designs are dominated by requirements for efficient cruise flight.

Table 1: 1995 technology baseline aircraft performance parameters.

Parameter	LRWB	BWB
Design Takeoff Gross Weight (lb.)	590,000	1,345,200
Zero Fuel Weight (lb.)	368,245	734,500
Passengers	305	800
Design Range (n.m.)	6300	8500
Rate of Climb at Sea Level (fpm)	3030	2900
Takeoff Field Length (ft)	11,000	10,000
Landing Field Length (ft)	12,500	8500
Life Cycle Cost - Design Mission (cents/available-seat-mile)	3.7	2.7
Estimated Aircraft Price	\$128M	\$192M

Simple performance analysis equations for rate of climb, range, takeoff and landing distance (Figure 3) and a single-term, zeroth-order, weight-based empirical life cycle cost equation were calibrated to existing Flight Optimization System (FLOPS) [Ref. 2] and life cycle cost models of the baseline aircraft. A total of six conventional widebody and two Blended Wing Body designs were evolved and analyzed.

The context within which the analysis was conducted is purposely simplified through the use of the selected performance equations. The reason for this simplification is twofold: first, to allow the reader to reproduce the results in a similar fashion with his/her own assumptions and, second, to demonstrate the first-order effects of particular performance parameters on an overall aircraft design. Weight breakdown and mission performance data were used from the FLOPS analysis results to determine and calibrate inputs to the simple performance equations. Once completed, the results from the simple performance analysis of the baseline models were considered to be the baseline performance for comparison, not the actual FLOPS performance results. This is especially important in flight segment-critical analysis, i.e., rate of climb and range analyses where average flight values are quoted in the results. With the baseline simple performance "models" in-hand, the input parameters were adjusted in correlation to the new technologies implemented on each evolutionary concept (the assumptions for which are stated with the concept discussions). Note that the vehicles WERE NOT resized - they were retrofitted with new components resulting in identical planforms. Therefore, if a wing was replaced with a more efficient but equivalent weight design, the takeoff gross weight of the aircraft was reduced due to fuel savings. The structural weight, design wing loading, and engine size of the aircraft were not changed to take advantage of the reduced takeoff gross weight. Empty weight changes were only made when components were added, deleted, or modified from the baseline design. Therefore these designs are not optimized -- their structure and engine size could potentially be reduced to correspond to the fuel savings achieved through increased performance. Our approach is limited in scope but provides conservative estimates with easily reproducible results. Additionally, note that the takeoff and landing distance equations do not account for FAR requirements in terms of balanced field length and missed approach and are therefore to be considered approximate at best.

Through performance parameters such as rate of climb, takeoff gross weight, fuel burn, takeoff and landing distances, approach speeds, and cost estimates are provided in the results. The reader can correlate these to higher-level system parameters inherent within the NASA Aeronautics and Space Transportation Technology Enterprise's Three Pillars for Success [Ref. 3]. First-order effects on the Pillar-One goals for increased safety, affordability, and national air transportation system capacity, as well as the goals for reduced emissions and aircraft noise, may be considered in the following relationships:

- 1) Safety increases are possible with decreased approach speeds.
- 2) Capacity can potentially increase when takeoff and landing distances decrease or when takeoff gross weight decreases. The first result can be attributed to the ability to build more, smaller runways. The second result can be achieved through decreased spacing made possible by vortex strength reduction at lower wing loading.
- 3) Affordability (from the standpoint of the consumer) may be proportional to the life cycle cost estimated savings stated in cents per available seat-mile.
- 4) Emissions reductions are largely proportional to fuel burn reductions without engine cycle improvements.
- 5) Noise reductions are perceived through increases in rate of climb or glideslope and elimination or reduction of noise sources. After takeoff, an increased rate of climb via enhanced high-lift performance without a change in jet velocity will decrease the noise "footprint" over an airport community through faster ground departure and reduced overflight distance. Similarly at landing, increased maximum lift capability without increases in airframe noise sources may be used to increase the glideslope and decrease the "footprint". An example might be the use of circulation control to eliminate the leading and trailing edge flaps. Note, however, that the acoustic effect of a technology such as circulation control on an integrated aircraft design is not known within the current body of literature.

Other non-performance-related effects of the SnAPII technologies are not explicitly discussed in this section but may be reviewed from the preceding section and implicitly deduced within the overall context of the Three Pillar goals.

Long Range Wide Body Evolutionary Concepts

LRWB Concept No. 1A

The first widebody evolutionary concept is shown in Figure 4. The concept employs the same two engines as the baseline, only mounted in Boundary Layer Ingestion (BLI) nacelles at the rear of the fuselage. This has several configurational effects, including the ability to shorten the landing gear, a requirement to move the wing rearward for both stability and control purposes and to move the landing gear closer to the now-displaced center of gravity. The BLI nacelles allow for a decrease in the parasite drag due to the fuselage at a cost of reduced engine efficiency. The positioning of the engines at the rear facilitates their use for thrust vectoring control. Though the method for vectoring high-bypass ratio turbofans is not definitively known, it may be possible through something as simple as nozzle-mounted turning vanes. The use of thrust vectoring conceivably allows the elimination of the empennage resulting in both drag reduction and structural weight savings but will require an increase in mounting hardware (and weight) relative to standard pylon-mounted nacelles. The shortened landing gear will result in a decrease in landing gear weight. A summation of the effects of these technologies on the input parameters of the simplified performance equations is given in Table 2. Note the assumption that the BLI penalty on engine performance is accounted for in the parasite drag input. The results from the analysis are recorded for comparison alongside the results from the other conventional evolutionary concepts in Table 8.

Table 2: Effect of SnAPII technology incorporation for LRWB 1A.

Parameter	Assumed Effect	Attributed to
$C_{D,o}$	-13%	Elimination of wing-pylon interference, removal of empennage, and implementation of BLI
C_D	-1%	$C_{D,trim}$ reduction due to implementation of thrust-vectoring control
Weight _{empty}	-3%	15% reduction in landing gear weight, elimination of empennage, doubling of nacelle weight to account for thrust vectoring

LRWB Concept No. 1B

Concept 1B (Figure 5) is identical to Concept 1A with exception of three additional SnAPII technologies. Wing-tip turbines are added for two purposes: to provide power for a suction pump powering a wing laminar flow control (LFC) system during cruise and to power a circulation control wing (CCW) during takeoff and landing. Additionally, it serves to break up the wing-tip vortex on approach for increased terminal area safety. LFC reduces the parasite drag attributable to the wing. The CCW provides increased high-lift capability for takeoff and landing. A summation of the effects of these technologies is given in Table 3. The results from the performance and cost analyses are, again, provided in Table 8.

Table 3: Effect of SnAPII technology incorporation for LRWB 1B.

Parameter	Assumed Effect	Attributed to
$C_{D,o}$	-25%	Elimination of wing-pylon interference, removal of empennage, and implementation of BLI and LFC
C_D	-1%	$C_{D,trim}$ reduction due to implementation of thrust-vectoring control
Weight _{empty}	-3%	15% reduction in landing gear weight, elimination of flaps and empennage, doubling of nacelle and air-conditioning weight to account for thrust vectoring and wing-tip turbines used for LFC/CCW, respectively
$C_{L,max}$	~+4%	Circulation control wing (CCW)
e (Oswald)	+5%	Load distribution tailoring with CCW and wing-tip turbine aspect ratio effect

LRWB Concept No. 2

Concept 2 (Figure 6) is very similar, in terms of technology content, to Concept 1B. Instead of using a wing-tip turbine to power the CCW, this concept uses engine bleed. This is facilitated by the use of a forward-swept wing (FSW) which reduces the amount of plumbing required to deliver engine bleed air to the powered lift system due to the proximity of the wing root to the tail-mounted engines. This configurational change eliminates the plausible use of wing-tip turbines and thus LFC is not implemented as in Concept 1B. It was assumed that the weight penalty (Table 4) for the FSW was not severe due to active control and composite construction. The results from the performance and cost analyses are provided for comparison to other LRWB concepts in Table 8.

Table 4: Effect of SnAPII technology incorporation for LRWB 2.

Parameter	Assumed Effect	Attributed to
$C_{D,o}$	-13%	Elimination of wing-pylon interference, removal of empennage, and implementation of BLI
C_D	-1%	$C_{D,trim}$ reduction due to implementation of thrust-vectoring control
Weight _{empty}	-1%	15% reduction in landing gear weight, elimination of flaps and empennage, doubling of nacelle weight to account for thrust vectoring and wing weight increase to account for forward swept wing penalty
$C_{L,max}$	~+4%	Circulation control wing (CCW)
e (Oswald)	+2%	Load distribution tailoring with CCW
Thrust _{takeoff}	-25%	Bleed compressor gases to blown flaps

LRWB Concept No. 3

Concept 3 (Figure 7) employs a variation of the Goldschmeid airfoil concept on the fuselage. The aircraft engines are again mounted aft on the fuselage in a manner similar to the previous three concepts. The Goldschmeid suction inlet is mounted forward of the engine inlet and the engine exhaust flow effects are assumed to parallel the Goldschmeid concept of trailing edge blowing. Again, wing-tip turbines are employed to provide power for a LFC system on the wing in cruise and to provide vortex reduction at landing. The empennage is eliminated due to thrust vectoring control and weight reductions similar to Concept 1A are assumed as indicated in Table 5. The results from the performance and cost analyses are provided for comparison to other LRWB concepts in Table 8.

Table 5: Effect of SnAPII technology incorporation for LRWB 3.

Parameter	Assumed Effect	Attributed to
$C_{D,o}$	-39%	Elimination of wing-pylon interference, removal of empennage, and implementation of LFC wing and Goldschmeid concept on fuselage
C_D	-1%	$C_{D,trim}$ reduction due to implementation of thrust-vectoring control
Weight _{empty}	-3%	15% reduction in landing gear weight, elimination of flaps and empennage, doubling of nacelle weight to account for thrust vectoring

LRWB Concept No. 4

This is almost a traditional wing tip-mounted engine aircraft concept (Figure 8). The engines employed are Advanced Ducted Propfans. Potentially, the large fan blades can be used to induce negative swirl in the tip vortex. This effect is assumed to dramatically reduce drag due to lift as indicated within the analysis input parameters shown in Table 6. The effects of spanload alleviation due to the tip mounted-engine on the wing weight and the increased size and weight of the vertical tail to account for engine-out conditions are assumed in the analysis inputs. The results from the performance and cost analyses are provided for comparison to other LRWB concepts in Table 8.

Table 6: Effect of SnAPII technology incorporation for LRWB 4.

Parameter	Assumed Effect	Attributed to
$C_{D,i}$	-20%	Wing-tip engine effect
Weight _{empty}	-1%	Wing weight reduction due to spanload alleviation and increase in vertical tail size and weight

LRWB Concept No. 5

The final conventional evolutionary concept is shown in Figure 9. This concept includes full span blown flaps and LFC powered by wing-tip turbines. The blown flaps system is assumed to result in a net weight reduction relative to the mechanical flap system. The blown flap system is assumed to be used to an extent during cruise flight in order to tailor the lift distribution. The wing-tip vortex strength on landing is reduced when the wing-tip turbines are locked in place. The analysis inputs for this con-

cept are shown in Table 7. The results from the performance and cost analyses are provided for comparison to other LRWB concepts in Table 8.

Table 7: Effect of SnAPII technology incorporation for LRWB 5.

Parameter	Assumed Effect	Attributed to
$C_{D,o}$	-10%	LFC powered by wing-tip turbines
Weight _{empty}	-1%	Balance of elimination of at least one flap element and track mechanism with addition of blown-flap pneumatics
$C_{L,max}$	~+5%	Internally blown-flap system
e (Oswald)	+5%	Wing-tip turbine aspect ratio effect and load tailoring with blown-flap system
Thrust _{takeoff}	-25%	Bleed compressor gases to blown flaps

The five LRWB concepts presented here are meant only to represent possible implementation strategies, not the entire design space made possible through SnAPII design philosophy. Table 8 demonstrates that significant improvements over the baseline LRWB model are possible through the synergistic implementation of propulsion-airframe integration technologies. L/D improvements can be tremendous and may result in significant fuel savings. Technologies that allow for elimination of structure achieve additional economies. The life cycle cost reductions are not extreme though the reader should note that these are due only to fuel savings and will increase with both optimum vehicle sizing and manufacturing and operating cost advantages of several SnAPII technology implementations.

Table 8: Comparison of effects from baseline for all evolutionary LRWB concepts.

Parameter	1A	1B	2	3	4	5
Takeoff Weight	-12%	-15%	-10%	-17%	-9%	-10%
Rate-of-climb	+28%	+45%	+30%	+57%	+10%	+23%
L/D _{cruise}	+13%	+22%	+15%	+34%	+8%	+9%
Weight _{fuel}	-16%	-23%	-17%	-30%	-11%	-12%
Takeoff Distance	-25%	-70%	-38%	-36%	-22%	-40%
Rotation Speed	--	-50%	-50%	--	--	-50%
Landing Distance	-1%	-80%	-80%	--	--	-84%
Approach Speed	--	-50%	-36%	+2%	+9%	-50%
Life Cycle Cost	-6%	-7%	-4%	-8%	-4%	-5%

Blended Wing Body Evolutionary Concepts

BWB Concept No. 1

The first evolutionary BWB concept (Figure 10) utilizes a Goldschmeid airfoil concept for its centerbody section and LFC powered by winglet-mounted tip turbines to provide large decreases in parasite drag. Additionally, the concept employs thrust vectoring for control and trim drag reductions. The analysis inputs for this concept are given in Table 9 and the results for both BWB evolutionary concepts are provided for comparison in Table 11.

Table 9: Effect of SnAPII technology incorporation for BWB 1.

Parameter	Assumed Effect	Attributed to
$C_{D,o}$	-50%	Implementation of LFC wing and Goldschmeid concept on fuselage
C_D	-1%	$C_{D,trim}$ reduction due to implementation of thrust-vectoring control
Weight _{empty}	+2%	Weight increase equivalent to doubling of nacelle and air-conditioning weights to account for thrust vectoring and LFC implementation, respectively
Mach _{cruise}	-12%	Mach number reduction is required due to extremely thick centerbody, however this also allows a reduction in wing sweep

BWB Concept No. 2

The second BWB concept (Figure 11) again uses winglet-mounted tip turbines to power a LFC system for the wing but includes a blown flap system for increased takeoff and landing performance. Additionally, the concept employs thrust vectoring for control and trim drag reductions. Analysis inputs are provided in Table 10 and the results are shown in Table 11.

Table 10: Effect of SnAPII technology incorporation for BWB 2.

Parameter	Assumed Effect	Attributed to
$C_{D,o}$	-25%	Implementation of LFC wing
C_D	-1%	$C_{D,trim}$ reduction due to implementation of thrust-vectoring control
Weight _{empty}	+2%	Weight increase equivalent to doubling of nacelle and air conditioning weights to account for thrust vectoring and LFC implementation, respectively
$C_{L,max}$	~+5%	Internally blown flap system
Thrust _{takeoff}	-25%	Bleed compressor gases to blown flaps

It is important to note that the BWB already includes many SnAPII and other advanced technologies. The BWB is a highly integrated configuration which makes the addition of features (or technologies) more difficult to integrate and synergistically exploit. However, as the results in Table 11 demonstrate, there is considerable potential for the inclusion of SnAPII technologies within the palette of design alternatives to return impressive benefits relative to more traditional design approaches.

Table 11: Comparison of effects from baseline for all evolutionary BWB concepts.

Parameter	1	2
Takeoff Weight	-18%	-9%
Rate-of-climb	+38%	+20%
L/D _{cruise}	+60%	+26%
Weight _{fuel}	-44%	-23%
Takeoff Distance	-41%	-29%
Rotation Speed	--	-50%
Landing Distance	+30%	-68%
Approach Speed	--	-50%
Life Cycle Cost	-8%	-4%

Summary

The results of this simplified analysis indicate that considerable progress towards NASA's aeronautics goals in global civil aviation may be achieved through the use of SnAPII technologies. This observation is more true for conventional configurations due to their relatively low levels of configuration and technology integration than it is for BWB configurations due to their inherently high levels of integration and resulting technological synergy. Including SnAPII technologies in the set of design technologies traditionally pursued in NASA system studies will allow further leveraging of both technology sets. With the additional use of those advanced technologies currently available due to NASA research (such as composites, improved engines, and advanced operational procedures), the impact on the aeronautics goals could well be dramatic.

References

1. Liebeck, R. H.; Page, M. A.; and Rawdon, B. K.: "Evolution of the Revolutionary Blended Wing Body Subsonic Transport," *Transportation Beyond 2000: Technologies Needed for Engineering Design*, NASA Conference Publication 10184, February 1996, pp. 431-460.
2. McCullers, L. A.: "Flight Optimization System Release 5.91 User's Guide", <http://avd00.larc.nasa.gov/flops/home.html>, July 1996.
3. NASA Office of Aeronautics and Space Transportation Technology, *Three Pillars for Success*, March 1997.

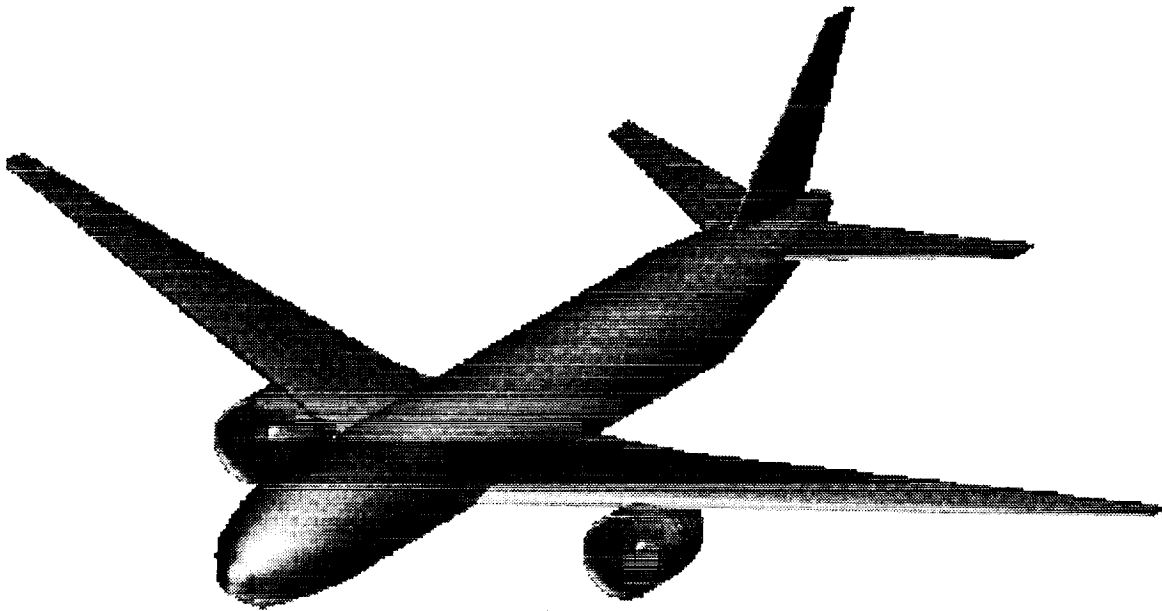


Figure 1. Baseline current-technology, long-range conventional widebody aircraft.

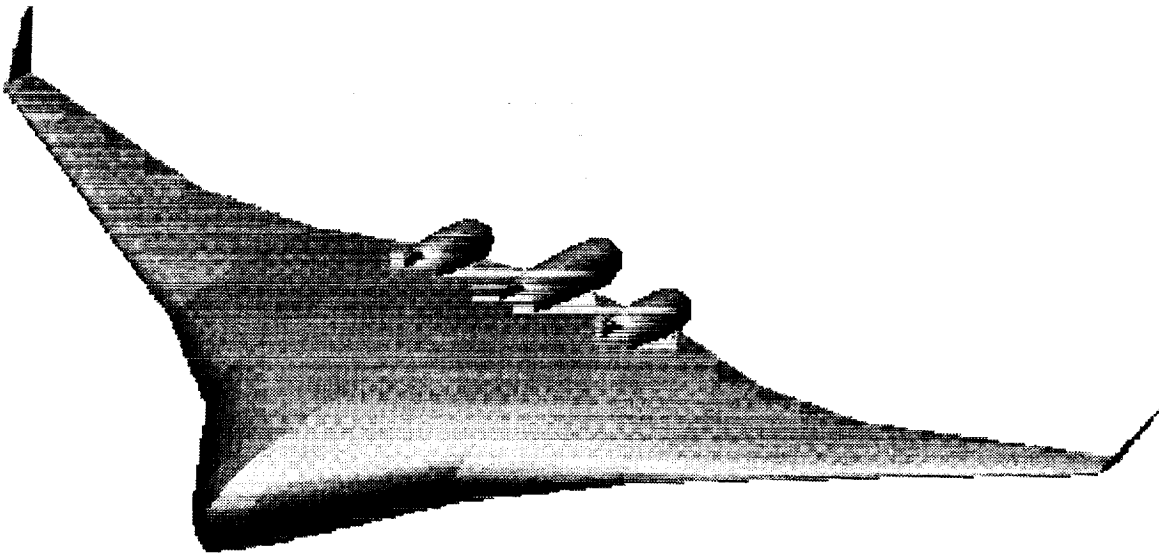


Figure 2. Baseline current-technology, aluminum construction Blended Wing Body aircraft.

$$R/C = \frac{(T - D)V_{\infty}}{W}$$

$$R = 2 \sqrt{\frac{2}{\rho_{\infty} S c_t}} \frac{1}{C_D} \sqrt{C_L} (\sqrt{W_0} - \sqrt{W_1})$$

$$s_{TO} = \frac{1.44 W^2}{g \rho_{\infty} S C_{L, \max} \{T - [D + \mu_r (W - L)]_{\text{average}}\}}$$

$$s_L = \frac{1.69 W^2}{g \rho_{\infty} C_{L, \max} [D + \mu_r (W - L)]_{0.7 V_{TO}}}$$

where:	c_t	thrust specific fuel consumption (lb/lb/sec)
	C_L	lift coefficient
	$C_{L, \max}$	maximum lift coefficient
	C_D	drag coefficient
	D	drag force (lb)
	g	acceleration due to gravity (ft/sec ²)
	L	lift force (lb)
	R/C	rate of climb (ft/sec)
	R	range (ft)
	s	field length (ft)
	S	reference wing area (ft ²)
	T	thrust (lb)
	V	velocity (ft/sec)
	W	aircraft gross weight (lb)
	μ_r	coefficient of rolling friction
	ρ	air density (slugs/ft ³)
with subscripts:	L	landing
	TO	takeoff
	0	start of cruise
	1	end of cruise
	∞	freestream conditions

Figure 3. Performance analysis equations used in this study.

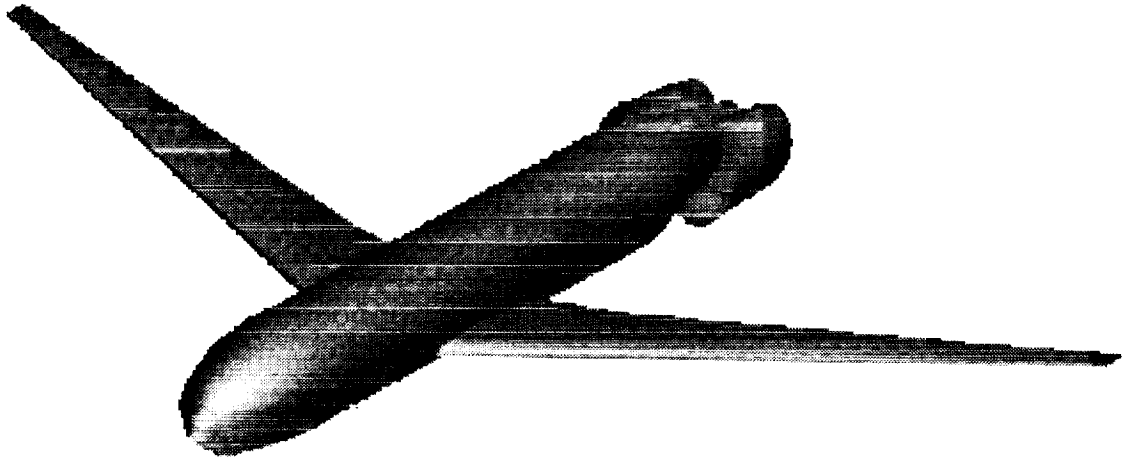


Figure 4. Long-range wide-body aircraft concept 1A.

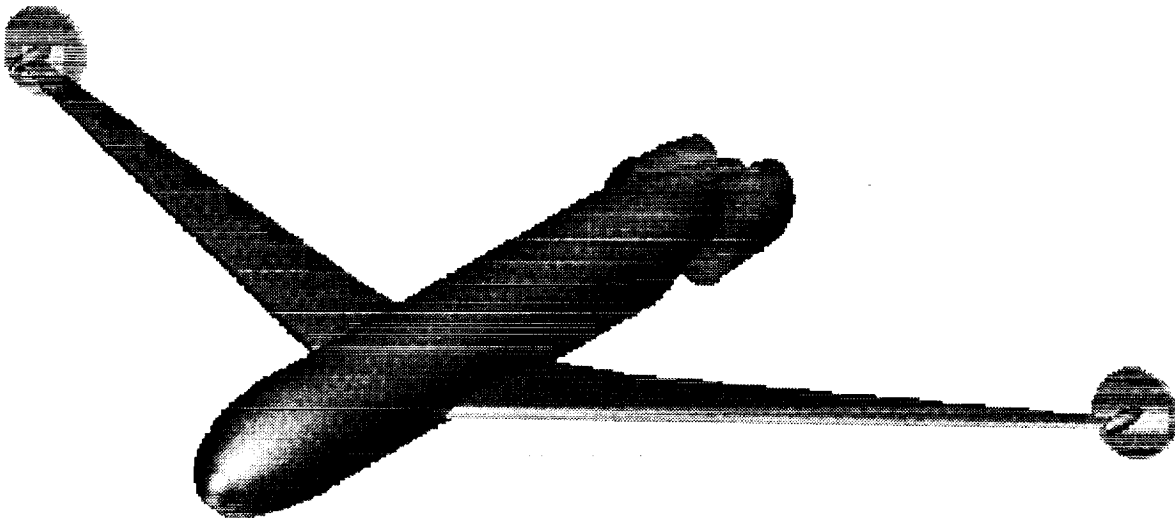


Figure 5. Long-range wide-body aircraft concept 1B.

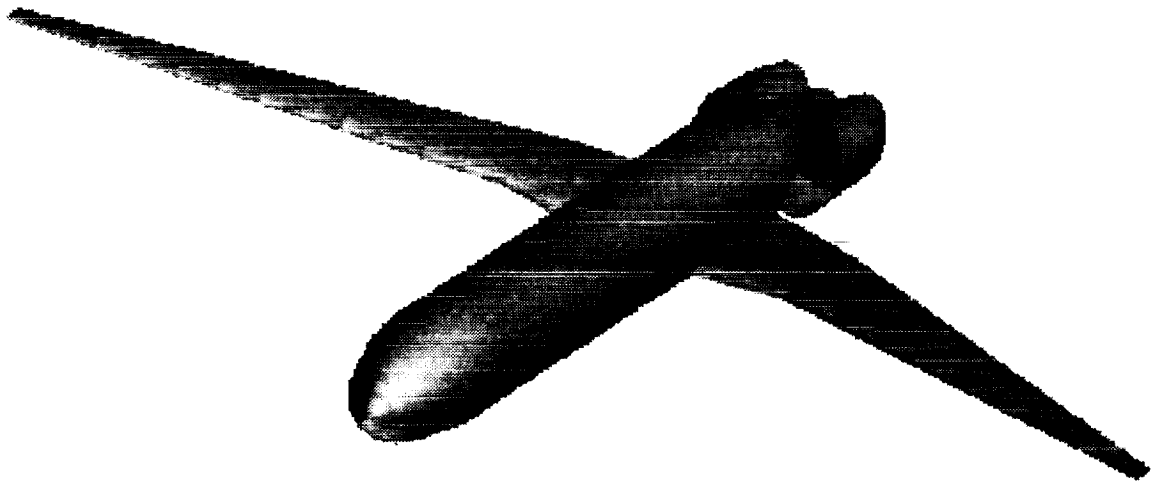


Figure 6. Long-range wide-body aircraft concept 2.

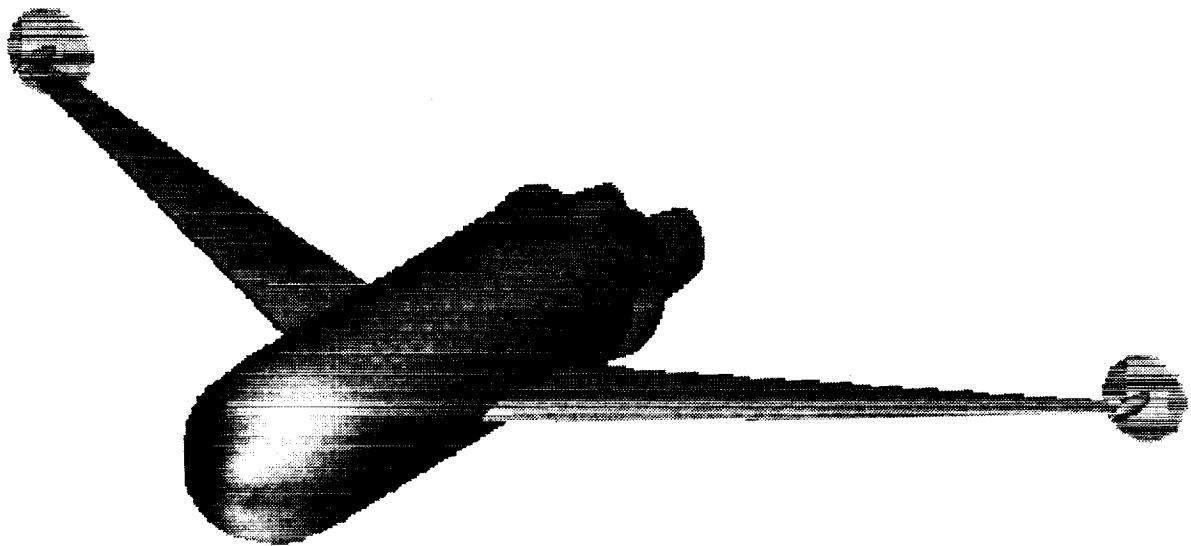


Figure 7. Long-range wide-body aircraft concept 3.

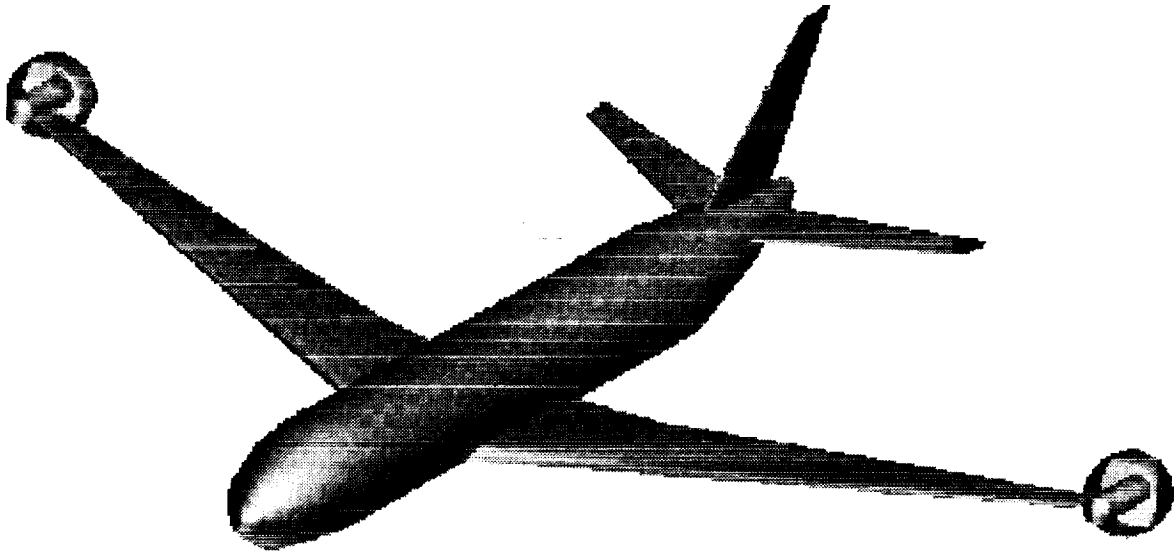


Figure 8. Long-range wide-body aircraft concept 4.

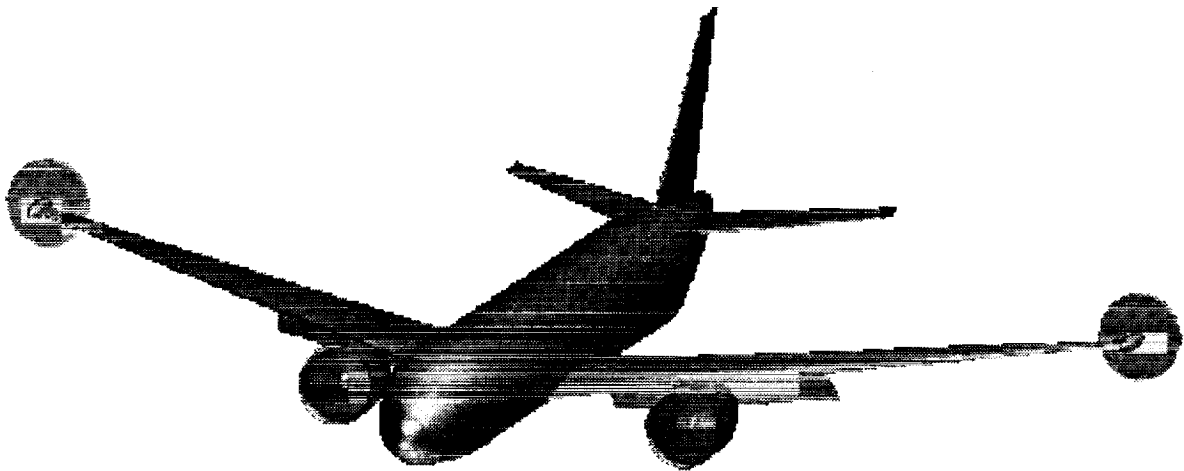


Figure 9. Long-range wide-body aircraft concept 5.

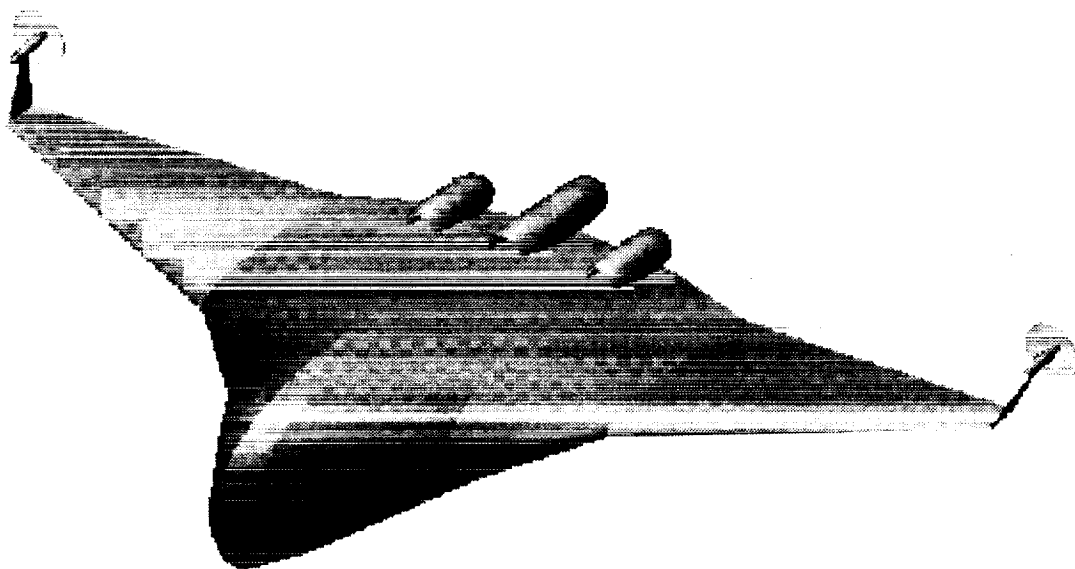


Figure 10. Blended wing-body concept No. 1.

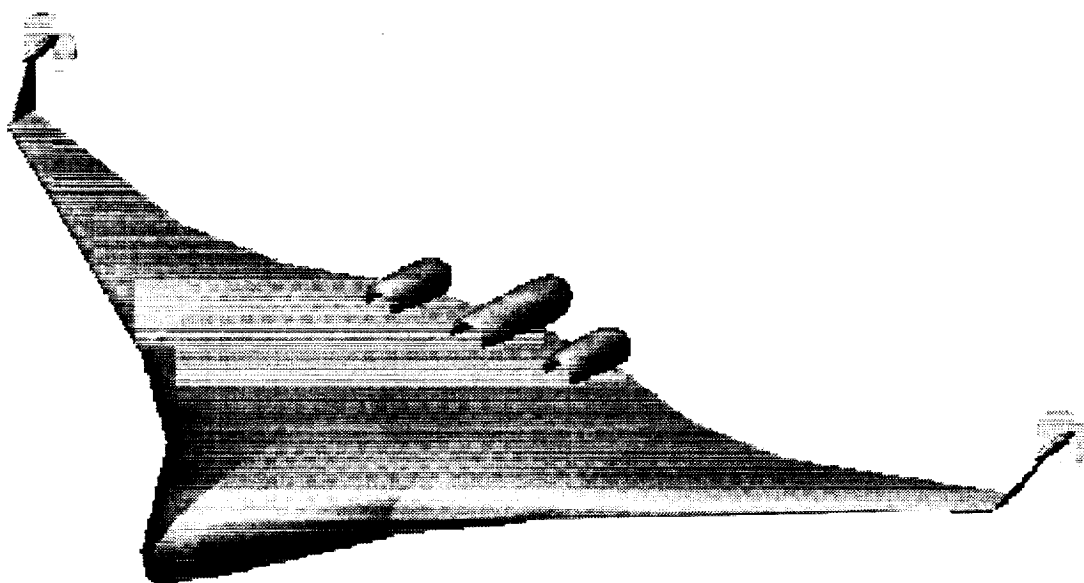


Figure 11. Blended wing-body concept No. 2.

Revolutionary Vehicle Concepts Utilizing SnAPII Technologies

The intent of this section is to exploit SnAPII technologies and other expected advances that may be available in approximately 20 years in order to develop ideas for future airplane concepts. There were no specific guidelines or constraints imposed on developing these concepts; members were free to think as far "out of the box" as they could. There is no detailed analyses of these concepts; the idea was to perform concept definitions using the knowledge presented in Technology Reviews and Evolutionary Vehicle Concepts sections of this document. Without question, these concepts require thorough systems analyses to determine their actual viability.

In order to facilitate a discussion of the relative benefits of each concept, a rating system was developed that attempts to relate its impact to the five goals described within Pillar One of the Aeronautics and Space Transportation Technology Three Pillars of Success. These five goals are to increase safety, reduce emissions, reduced noise, increase capacity, and improve affordability. For each of these goals, the following rating system was used:

- +2 Concept has a **definite positive impact** on this goal
- +1 Concept has a **perceived positive impact** on this goal
- 0 Concept has a **no impact** on this goal
- 1 Concept has a **perceived negative impact** on this goal
- 2 Concept has a **definite negative impact** on this goal

For each of the concepts, a basic description of the concept (mission, size, etc.) will be presented. This will include the SnAPII technologies that will be employed, any other unique or significant features, and a ratings assessment based on the criteria established above.

Blended, Forward-Swept-Wing Body (BFSWB) Concept

The Blended, Forward-Swept-Wing Body (BFSWB) concept (figures 1 and 2) is a long-range transonic commercial passenger/cargo transport. As drawn, the concept is an 800-passenger, 7000 nautical mile range aircraft. Passengers are seated in a two-deck, three-class arrangement within the centerbody, cargo is outboard of the passengers, and fuel is in the wing.

Several SnAPII features are incorporated in this design. A circulation-controlled wing (CCW) powered by an auxiliary power unit is used to provide high C_L at takeoff and landing. The BWB in all of its permutations has low wing loading, so the CCW would enable very short takeoff runs and landing rollouts, relative to other very large subsonic transports. The three aft-mounted high-bypass ratio turbofan (or advanced ducted prop) engines incorporate boundary layer ingestion (trades increased specific fuel consumption, known as sfc, for reduced drag), thrust vectoring and reversing (allows simpler controls and less systems power consumption, plus reversing works synergistically with CCW for reduced field length requirements), and smart inlet and nozzle technology (reduced weight, noise and sfc). Laminar flow control, both natural and active, can be utilized on this configuration.

A summary of the ratings for this concept against the five aeronautical goals is provided below.

to Increase Safety	to Reduce Emissions	to Reduce Noise	to Increase Capacity	to Improve Affordability
+2	+1	+2	+2	+2
NOTE: Ratings range from +2 (definite positive impact) to -2 (definite negative impact).				

Safety. The BFSWB has some inherent safety features. Debris from an uncontained disk failure in the aft-mounted engines cannot penetrate the pressure vessel, the main wing structure, or the fuel tanks. In addition, staggering the engines helps guard against engine fratricide. Careful integration of the forward-swept design may yield a statically stable configuration with more center-of-gravity range than an aft-swept BWB. The thrust vectoring system provides an inherent propulsion-controlled aircraft (PCA), with normal control surfaces as backup. Note that although the escape paths are short, passenger egress may be a safety issue for some situations on all BWB configurations

Emissions. The clean design (tailless, minimal wetted area per passenger) requires fewer and smaller engines than equivalent technology conventional configurations. Performance improvements from the CCW, laminar flow, and smart inlets/nozzles will reduce emissions from first and second-order sizing effects.

Noise. The upper surface inlets on the BWB designs provide a large decrease in perceived forward-radiated noise, since the centerbody acts as a large shield. Smaller engines, fewer/smaller control surfaces, high takeoff/landing C_L , and smart inlet/nozzles will all reduce the community noise impact.

Capacity. The BFSWB, as previously noted, is an 800-passenger concept. It will require half as many airport operations as today's largest aircraft (747-400) to move the same number of passengers. The low wing loading of this design will also reduce the wingtip vortex strength, allowing less in-trail spacing between aircraft.

Affordability. Affordability correlates almost directly with weight. All of the SnAPII technologies work in harmony to improve performance (yielding a smaller, lighter aircraft for the same mission) and/or directly decrease weight. The large size of the BFSWB also helps with affordability, since more revenue passenger miles are generated per pound (both of fuel burned and aircraft purchased/maintained). The concept itself also yields affordability improvements through advanced manufacturing processes (e.g., unhandled parts, in-place assembly).

Distributed Engine Regional STOL (DERS) Concept

The Distributed Engine Regional Short-TakeOff and Landing (DERS) Concept (figures 3 and 4) is short-to medium range (500-1500 miles) transport capable of carrying 100-200 passengers. The DERS concept incorporates very revolutionary and interesting technologies. Passengers are seated in a two-class arrangements. The fuselage utilizes structurally integrated transparent composite fuselage panels for the viewing pleasure of the passengers. The first class cabin is a full-view section. The operator section with synthetic vision is located in the aft section of the aircraft. The airplane has no tails and employs an array of mini-engines integrated with the wing allowing tailoring of lift distribution, increased redundancy and providing low-speed lift augmentation for short takeoff and landing field performance. These low diameter engine components produced mostly high frequency noise that is actively controlled at the engines inlet and nozzle through the use of "smart materials". These new-generation materials have shape changing capability and they will be used in the wing's leading and trailing edges to provide roll control and to tailor off-design performance to flight condition.

The DERS concept utilizes some SnAPII technologies. The tail engine uses the boundary layer ingestion inlet. In addition this tail engine is really another array of mini-engines integrated with the inlet/nozzle deflectors to produce a coanda effect for augmented thrust vectoring.

An assessment of the Distributed Engine Regional Short-TakeOff and Landing concept with respect to the five goals is contained in the following table.

to Increase Safety	to Reduce Emissions	to Reduce Noise	to Increase Capacity	to Improve Affordability
+2	-1	+1	+2	+2
NOTE: Ratings range from +2 (definite positive impact) to -2 (definite negative impact).				

Safety. The use of mini-engines distributed along the wing and in the tail engine section increase redundancy in case of engine failure. Load distribution tailoring, enabled by the use of a very high aspect ratio wing in conjunction with propulsion optimization with use of smart materials, produce alleviation of gust load/flutter problems to the structure of the wing.

Emissions. A mild negative impact to emission is assumed due to the reduced efficiency of the small scaled engines utilized in these concepts.

Noise. The elimination of flap/slats systems will greatly contribute to reduction in noise during landing and take-off operations. However, additional high frequency noise may be present, due to the additive nature of the noise from the individual jet engines.

Capacity. The efficient arrangement of passengers with the utilization of transparent composite fuselage panels contributes to an increased capacity. The full integration of the propulsive system for tailoring of off-design performance to flight condition contributes to more capacity because passenger revenue per mile will undoubtedly increase.

Affordability. The use of small interchangeable engines will reduce the operating cost and time delays due to mechanical problems at airports. Utilization of smart materials reduce weight because of the elimination of complex and heavy mechanical systems such as flaps/slats. In additions these material are light-weight so that overall empty weight of the aircraft will be reduced. Manufacturing savings will be realized because the outboard wing will be a constant symmetric section enabling extrusion manufacturing techniques.

Goldschmied Blended Joined Wing (GBJW) Concept

A blended-wing-body, joined with an aft-mounted forward-swept-wing, forms a blended-joined wing and is the basic concept for this large capacity, transonic transport. It will have winglets and three engines but no tail. Two engines are mounted aft and a third is associated with the Goldschmied suction blowing system. See figures 5 and 6 for a three view of the perspective and configuration, respectively.

SnAPII technologies and other features associated with this configuration are listed here. A Goldschmied suction-blowing system will be utilized for the promotion of laminar boundary layer over the thick part of the configuration. This will be needed over the top part of the wing. Circulation control over the slender portions of the wings, smart inlet/nozzle shaping for the engines, and propulsion control of the aircraft are also used.

The configuration should allow for easy egress, minimize tip vortices, and a minimization of unique wing parts through proper attention to the design and manufacturing process details.

An assessment of the Goldschmied Blended Joined Wing concept with respect to the five goals is contained in the following table.

to Increase Safety	to Reduce Emissions	to Reduce Noise	to Increase Capacity	to Improve Affordability
+2	+1	+2	+2	+2
NOTE: Ratings range from +2 (definite positive impact) to -2 (definite negative impact).				

The justifications of the ratings in the table are as follows:

Safety. Thrust vectoring, coupled with propulsion control of the aircraft, and easy egress from vehicle should enhance its safety of operation, even during times of an engine failure and crash landing. Moreover, with all engines located aft, the passengers should be better protected from engine blade failure.

Emissions. The reduction from four engines to two on the wing and one to provide for the suction/blowing system will lead to an aircraft with fewer emissions.

Noise. The reduction from four engines to two on the wing and one to provide for the suction/blowing system will lead to a quieter aircraft. Also, circulation control -- driven by the third engine -- will allow the aircraft to get higher faster during take-off and remain higher longer during landing, thereby reducing community noise. Moreover, the airframe noise should be reduced since most of it will have laminar flow.

Capacity. Due to the thrust vectoring, circulation control, along with reduced tip vortices, the aircraft should be able to get in and out of the airports more quickly. Moreover, during the take-off or landing portions the circulation control and thrust vectoring can be used to accommodate the trailing vortex systems from other aircraft.

Affordability. Reductions in the number of engines and the use of more common parts for the wings will lead to a reduction in cost of manufacture. Moreover, the use of laminar flow over most of the wings should reduce the direct operating costs.

Modified Chaplin V-Wing (MCVW) Concept

The basic concept is a modification to the Chaplin V-wing [ref. 1] and is envisioned as a replacement for the B-757/767 class of transonic transports. A conceptual three-view layout along with a perspective sketch are presented in figures 7 and 8. Note that the passengers sit in the wing, as shown in figure 9. As shown, the concept will have winglets and three engines but no horizontal tail. The engines are located in the root region. Pitch control is through thrust vectoring of these engines and directable, distributed trailing-edge blowing, also shown in figure 9. Lateral control is through the rudders on the winglets and differential vectoring/blowing.

SnAPII technologies and other features associated with this configuration are listed here. A Goldschmied suction-blowing system will be utilized for the promotion of a laminar boundary layer over the center part of the configuration coupled with boundary layer ingestion for the restarted boundary layer. Smart inlet/nozzle shaping for the engines, including thrust vectoring, and tip turbines are to be used. The latter are employed as an energy source for boundary-layer suction and promotion of significant laminar flow on the main wings. The flow removed will be used to provide positive static thrust along the wing trailing edge, a la Goldschmied.

The configuration should minimize tip vortices, as well as minimize unique wing parts through proper attention to the design and manufacturing process details. In particular, many wing sections may be similar provided the twist associated with the wing can be properly taken into account.

An assessment of the Modified Chaplin V-Wing concept with respect to the five goals is contained in the following table.

to Increase Safety	to Reduce Emissions	to Reduce Noise	to Increase Capacity	to Improve Affordability
0	+1	0	+1	+1
NOTE: Ratings range from +2 (definite positive impact) to -2 (definite negative impact).				

The justifications of the ratings in the table are as follows

Safety. Three engines instead of two should be a plus but this aircraft may have unusual flying characteristics; plus it has such a small rotation angle that thrust vectoring will be required for takeoff and landing.

Emissions. Reductions in drag due to improved boundary-layer flow will lead to a reduction in emissions. This is possible because during cruise the tip-turbine powered suction/blowing system will provide sufficient net static thrust so that the three main engines can be throttled back and yet have the aircraft maintain its design Mach number. Less required jet thrust means fewer produced emissions.

Noise. The sources of noise are the use of three engines instead of two, small rotation angle, and the tip turbines. Noise reduction comes from much laminar flow over the airframe and through the use of thrust vectoring. The net effect is for no change in noise level.

Capacity. Due to the thrust vectoring and minimizing trailing vortices, the aircraft should be able to get out of the airports more quickly once airborne. Landing could be accomplished by maintaining cruise altitude until just prior to the airport, then with thrust vectoring maintain attitude through a controlled stall ending at the beginning of runway in a low attitude flair; also know as ATOPS.

Affordability. The use of more common parts for the wings will lead to a reduction in cost of manufacture. Moreover, the use of laminar flow over most of the wings should reduce the direct operating costs.

Reference.

1. Chaplin, Harvey R.: "Application of Very Thick BLC Airfoils to a Flying Wing Type Transport Aircraft". SAE Tech. Pap. Ser. No. 901992, Oct. 1990.

SnAPII Civil Tilt-Rotor Concept at 2025 (SC2025)

The SnAPII Civil Tilt Rotor (SC2025) concept (figures 10 and 11) is a regional commercial transport concept that could be configured to seat from 30 to 60 passengers. As with current civil tilt rotor (CTR) concepts, the design is intended to increase passenger utility of air travel through increased access. This is accomplished by the ability to takeoff and land vertically and hover for extended periods of time, allowing the vehicle to access locations that are not equipped with runways. This capability enables point-to-point transportation, high-speed transportation to constrained locations such as downtown areas of major cities, off-loads capacity from major airports, and makes more efficient use of passenger time.

The key technology requirement for the SC2025 is the accelerated development of mini-turbine engine technology beyond the current cruise missile engines and Williams FJX turbofan. Engines that measure inches in fan diameter are envisioned that can be mass produced in large quantities and take advantage of advanced manufacturing technology and automation. The engines are conceptualized to be relatively standard such that thrust requirements can be met by adjusting the number of engines integrated with the configuration rather than developing new engines for varying thrust requirements. Due to high-rate mass production and standardization, the engines could potentially be very inexpensive (\$100's) and therefore easily replaced, remanufactured, and recycled.

The mini-turbines are integrated with the SC2025 rotor blades to provide a powered-lift/augmented thrust blade capable of unprecedented disk loading and control. If engines are positioned across the rotor blades with inlets and nozzles that span the entire upper surface, they can be used to create a super-circulation effect at low-incident blade speeds. This effect is due to the acceleration of the flow over the blade upper surface into the engines and the ejection of engine exhaust at speeds that would normally be greater than blade trailing-edge flow speeds. The supercirculation effect will also "vector" the thrust flow with the streamlines creating additional lifting forces. For a range of blade speeds the blade may be inseparable, creating a situation allowing extremely high lift coefficients and very low blade rotation rates. This capability allows for smaller and lighter rotor blades for a given takeoff gross weight vehicle. The use of on-rotor engines eliminates the need for a rotor drive system and gearing because the engine thrust provides rotational energy. The use of multiple engines engenders redundancy and eliminates the nominal CTR requirement of cross-shafting mechanisms to account for engine-out performance. If active control of the engines is used, the blade lift distribution may be tailored for specific blade efficiencies. This capability may be traded-off against rotor noise reductions accomplished through the hyperacceleration of the tip vortex flows using the mini-turbine nearest the tip. Aircraft morphing technologies such as shape memory alloys may be used to selectively and "intelligently" shape blade leading and trailing edges as well as inlet and nozzles for on- and off-design conditions, enabling increased engine efficiency and blade aerodynamics as well as to allow simplifications in manufacturing design. The combined usage of morphing technologies and on-demand blade-lift distribution tailoring provides the opportunity for mechanism-less cyclic and collective control while in helicopter mode. The same effects used to provide powered lift from the rotor blades for helicopter mode are available to provide augmented thrust as the rotors tilt forward to airplane mode. Overall, these affects may significantly decrease the empty weight and both airframe and maintenance cost of the vehicle as well as increase the combined propulsive-aerodynamic efficiency to reduce fuel requirements.

Other SnAPII technologies used on the SC2025 concept are included in the aft-fuselage nacelle. This nacelle contains additional mini-turbines that ingest the fuselage boundary layer for drag reduction, utilize morphing nozzle features and tailored distribution of thrust to effectively provide "thrust vectoring" control and eliminate the requirement for a tail. This nacelle is extremely bluntly shaped, using morphing technologies such as synthetic jets and on-demand vortex generation to provide separation control both internally to reduce duct losses and externally to reduce profile drag. The use of these technologies has the potential to further increase the propulsive-aerodynamic efficiency of the airframe and lower both the empty weight and overall cost.

An alternative implementation of these technologies is depicted in figures 12 and 13. The integration is identical to the previously described concept except that, while in airplane mode, the rotor blades will rotate into the flow (feather), placing the rotor-mounted engines directly in the desired thrust line. This eliminates the need to use the rotors as propellers for airplane mode and instead relies on unaugmented engine thrust alone to power the vehicle.

A summary of the ratings, which are the same for this concept and the alternative concept, against the five aeronautics goals is shown below.

to Increase Safety	to Reduce Emissions	to Reduce Noise	to Increase Capacity	to Improve Affordability
+1	0	+1	0	+2
NOTE: Ratings range from +2 (definite positive impact) to -2 (definite negative impact).				

Safety. The SC2025 enjoys much higher propulsive redundancy than any state-of-the-art vehicle due to its multitude of mini-turbine engines. This provision eliminates requirements for cross-shafting or autorotation descent. Additionally, the thrust-vectoring control both in helicopter and airplane mode may provide a much greater degree of maneuverability than currently possible.

Emissions. The SC2025 will likely be more fuel efficient than both contemporary helicopters and CTRs through its superior performance. However, it is not evident that the mini-turbines can achieve a similar level of emissions reductions, on a per pound of thrust basis, as is forecast for larger high-bypass ratio turbofans. These effects may well cancel each other out.

Noise. Lower blade tip speeds during takeoff and landing operations combined with the possible dispersion of the tip vortex due to the hyperacceleration of the tip flow with a mini-turbine may possibly result in a significant noise reduction of the SC2025 compared to contemporary helicopters, regional airplanes, and the CTR. However, additional high frequency noise may be present, due to the additive nature of the noise from the individual jet engines.

Capacity. The SC2025 is not perceived to offer greater capacity increases than those forecast to be enabled by the (baseline scenario) introduction of the CTR during the next twenty years.

Affordability. It is perceived that engine life cycle costs may be significantly reduced using standardized, mass produced, and inexpensive mini-turbines. The removal of the power train, cross-shafting requirement, and empennage and the increased propulsive-aerodynamic efficiency should combine to achieve significant reductions in both airframe size/weight and fuel requirements resulting in considerable airframe-related life cycle cost reductions.

SnAPII Twin Fuselage (STF) Concept

The SnAPII Twin Fuselage (STF) concept is a transonic commercial passenger and/or cargo transport that could be used for regional hub, transcontinental, and trans-oceanic flights. This concept is shown in a perspective rendering (figure 14) and a three-view orthographic drawing (figure 15). The pilot would be located in the nose of one of the fuselages, and first-class seating would occupy the nose of the other.

This concept utilizes many SnAPII and aerodynamic features. The twin fuselages would be separated by a circulation-controlled wing (CCW). This CCW, powered by an auxiliary power unit, would provide high C_L at takeoff and landing when employed and would morph and/or actuate into a wing cross section that provides better performance at cruise conditions. A sketch of the CCW cross section showing areas that could be altered is presented in figure 16. The leading and trailing edges of the relatively blunt CCW wing would be conformed with a more efficient cruise shape, and the circulation control slot on the upper surface would be closed. The STF concept would include two tail-mounted engines, one at the end of each fuselage. These engines would take advantage of fuselage boundary-layer ingestion, smart inlet and nozzle technology, and thrust vectoring/reversing for both performance enhancement and configuration control. Finally, wing tip turbines would be mounted on the high aspect

ratio outer wings to provide a vortex wake hazard reduction at takeoff and landing, as well as an energy generation device that would be used to power the suction boundary-layer laminar-flow control on the outer portions of the wing. Minimal flaps are incorporated and are utilized primarily for backup control following an engine out.

A summary of the ratings for this concept against the five aeronautics goals is provided below, followed by justification describing each rating for the STF concept.

to Increase Safety	to Reduce Emissions	to Reduce Noise	to Increase Capacity	to Improve Affordability
+2	+1	+2	+2	+2
NOTE: Ratings range from +2 (definite positive impact) to -2 (definite negative impact).				

Safety. The STF incorporates many features that increase safety, including wing-tip turbines that provide vortex wake hazard reduction during takeoff and landing, the main engines are located far away from passengers, the fuselages allow for plenty of egress routes in the event of an emergency.

Emissions. The STF concept may require smaller engines due to aerodynamic performance improvements (no vertical tails, deployable/morphing CCW, high AR wings with laminar flow) and the use of smart inlets and nozzles, thus possesses a perceived positive impact.

Noise. The noise generated by the STF concept would be less due to smaller engines (see above), shielded inlets, engine placement in the back, fewer and smaller flaps, and high C_L at takeoff and landing. The high C_L at low speeds will allow quicker climbout and descent in order to reduce community noise.

Capacity. The capacity of this concept would definitely be increased because of the use of twin fuselages, single- and/or dual-gate ingress and egress, and tip vortex hazard reduction that would increase airport throughput.

Affordability. This concept improves affordability by utilizing existing technology enhancements, using the propulsion system to control the aircraft (thrust vectoring), and using extruded CCW parts to reduce manufacturing costs.

An alternative twin-fuselage concept called the Inboard Wing is shown in figures 17 and 18. This concept trades the aspect ratio provided by the outer wing panels for a reduction in induced drag. The fuselages act as endplates for the wide-chord wing between them (hence the name), and working in conjunction with the canted tails, greatly reduce the wing tip vortices. The tails are canted inboard and actually produce thrust due to their interaction with the weak wing vortex that does remain. Compared with the "standard" twin fuselage design, the Inboard Wing should have enhanced safety and capacity metrics due to negligible wing tip vortices and improved affordability due to reduced drag. Other twin fuselage concepts include replacing the outboard wing panels with a C-wing for increased span efficiency, or possibly an Inboard Wing biplane that uses a forward and an aft wing between the fuselages for increased lifting force and/or center-of-gravity margins. Ratings are the same as for the standard twin fuselage concept.

Trans-Oceanic Air-Train (TOAT)

The Trans-Oceanic Air Train (TOAT) is a vehicle system concept (figures 19 and 20) designed for long range transport of large quantities of cargo. The system design is optimized for low cost operational procedures, high volume, minimal infrastructure requirements, and easy on/off loading of standard 8x8x20 foot shipping containers. The vehicle system consists of two distinct vehicle designs

which use advanced technology to make the in-flight, wing tip-to-wing tip connection which enables the system's superior long range performance.

The TOAT system concepts of two unique vehicle designs, the Lead and the Mule. Each Mule vehicle will rendezvous with the Lead vehicle and connect to either the Lead or another Mule to form the cruise configuration. The cruise configuration is a low transonic Mach number, high aspect ratio, span-loaded design intended for extremely fuel efficient flight and low structural running loads. The range of the cruise configuration is dictated by the both the fuel carrying capacity of the Lead vehicle and the number of Mule vehicles being ferried because the majority of the fuel volume is contained within the Lead vehicle. To adjust range, one simply adds or subtracts Mule vehicles as appropriate within the limits of the Lead vehicle's fuel capacity. Tanker versions of the Mule vehicles could be developed to enable extremely high-capacity, longer range versions of the system.

The Mule aircraft is a simple zero sweep, high thickness-to-chord ratio, unitary taper flying wing. It is intended to be uninhabited and capable of carrying significant numbers of the standardized 8x8x20 shipping containers currently used by the trucking/ocean-freight shipping industry. The zero sweep design allows for straight one-end loading and opposite-end unloading of cargo for excellent turn-around time operations. Due to its simple configuration, loading ramps and equipment could easily be integrated with the vehicle. The Mule would be powered by Advanced Ducted Propfans (ADPs) mounted on pylon structures incorporating shape change, "morphing" technology. The adjustability of these pylons will enable high side-to-side thrust "vectoring" with the ADPs during high sideslip in-flight connection procedures and precise maneuverability and trim control. In addition, the Mule design will incorporate morphing technology for leading edge and trailing edge shape adjustments for high-lift, trim control, roll maneuvering, and lift distribution tailoring.

The connection mechanisms may be made from "morphing" derived "inch worm" devices for high-speed, high-precision actuation and to provide aerodynamic seals at the connection point between Mules. The vehicles will also benefit from the use of engine-powered pneumatic control in the form of wing-tip blowing for precise maneuvers and suction for connection seals. Each Mule conceptually carries only enough fuel to provide takeoff, formation rendezvous, connection procedures, abort to alternate airstrip, and landing operations. The fuel for cruise flight, the crew, and the command, control and communications functions are all provided via the Lead vehicle. Each Mule will carry only enough onboard sensors to provide necessary operating data to the Lead for functional analysis and control and to allow autonomous flight following an aborted connection or in-flight failure.

A summary of the ratings for this concept against the five aeronautics goals is shown below.

to Increase Safety	to Reduce Emissions	to Reduce Noise	to Increase Capacity	to Improve Affordability
0	+2	0	+2	+2
NOTE: Ratings range from +2 (definite positive impact) to -2 (definite negative impact).				

Safety. There are obvious questions and concerns over the adequacy of actively controlled connection mechanism, close-in high-sideslip flight, fault tolerant structures, etc. It is perceived that advances in localized smart structures, parallel computational processing, sensor design, and artificial intelligence may be able to overcome these technical challenges. Finally, it is not apparent at this time whether politics would allow populated area overflight of these large RPVs unless military usage of RPVs and uninhabited aircraft proves successful.

Emissions. The TOAT system should enjoy outstanding aerodynamic performance due its span-loaded, high aspect ratio cruise configuration and moderate cruise Mach number. The use of ultra-high bypass ratio ADPs should generate very efficient levels of specific fuel consumption. Combined, these

two effects should realize a dramatic reduction in aircraft emissions on a per pound of cargo per revenue mile basis.

Noise. The TOAT vehicles will require very high levels of takeoff thrust due to their equally high takeoff gross weights. The engines will likely be sized to this criterion (assuming typical field lengths) and will produce high levels of effective perceivable noise level (EPNL). For landing operations, the nominal wing loading will possibly produce reasonable performance though the number of landing gears may become significant noise sources. Overall, the noise performance for these vehicles is not likely to be superior to the current state-of-the-art primarily due to configurational effects.

Capacity. On a ton equivalent unit (TEU) basis per airport flight operation, the TOAT system is capable of carrying far more cargo than current freighters. The system is also capable of extremely rapid turn-around due to its load-on/load-off of standard containers and parallel processing of Mule vehicle capabilities.

Affordability. The general layout of the Mule vehicles is intended to promote exceptional affordability for manufacturing through constant-cross sections, straight lines, part commonality, and standard configuration regardless of payload and range capacity. The fuel efficiency of the cruise configuration should be considerably greater than current aircraft due in part to spanloader structural efficiency, high aspect ratio aerodynamics, tailless design, and the propulsive efficiency of the ADPs. Finally, life cycle cost would be impacted in a dramatic fashion due to very efficient operating procedures, minimal use of flight crew, and large cargo capacity.

Summary

The out-of-the-box, blue-skies brainstorming exercise to create potential concepts that would utilize SnAPII technology resulted in seven distinct concepts and at least two other alternatives. A ratings summary of all of the concepts follows. Remember that the ratings denote the committee's perception of the relative impact that the concept would make in the goals listed along the top of the column. While detailed aircraft systems analysis is required on every concept, it is important to note that the conclusion from this effort is that the potential truly exists for exploitation of synergistic interactions between the airframe and propulsion systems.

Concept	to Increase Safety	to Reduce Emissions	to Reduce Noise	to Increase Capacity	to Improve Affordability
BFSWB	+2	+1	+2	+2	+2
DERS	+2	-1	+1	+2	+2
GBJW	+2	+1	+2	+2	+2
Modified Chaplin V-wing	0	+1	0	+1	+1
SC2025	+1	0	+1	0	+2
SC2025, Version 2	+1	0	+1	0	+2
STF	+2	+1	+2	+2	+2
STF, Version 2	+2	+1	+2	+2	+2
TOAT	0	+2	0	+2	+2
NOTE: Ratings range from +2 (definite positive impact) to -2 (definite negative impact).					

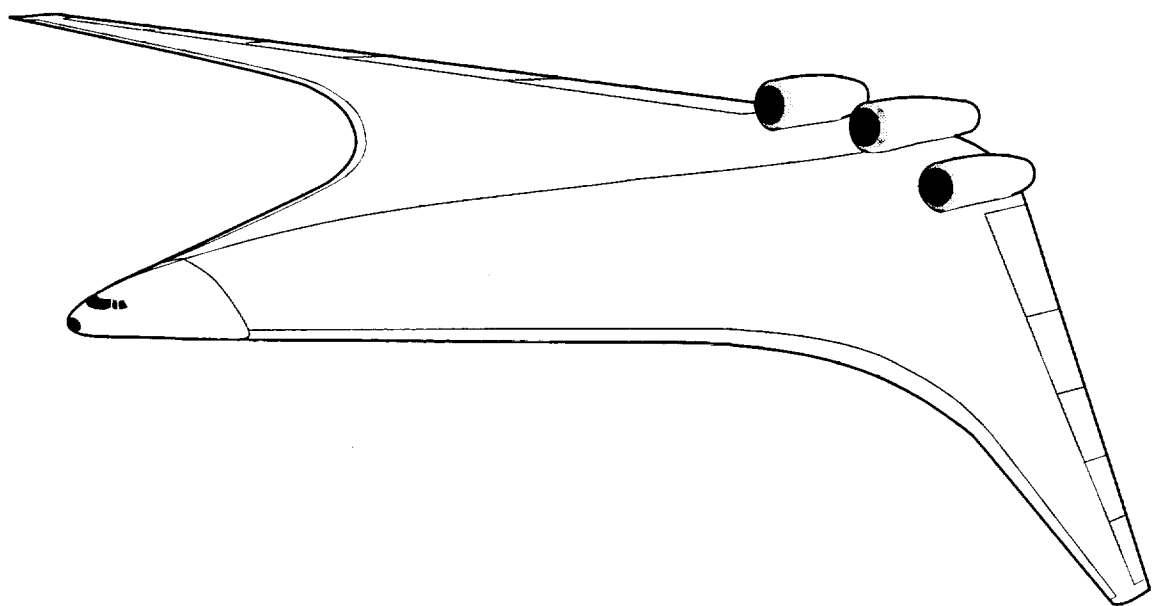


Figure 1. Blended, forward-swept-wing body concept perspective drawing.

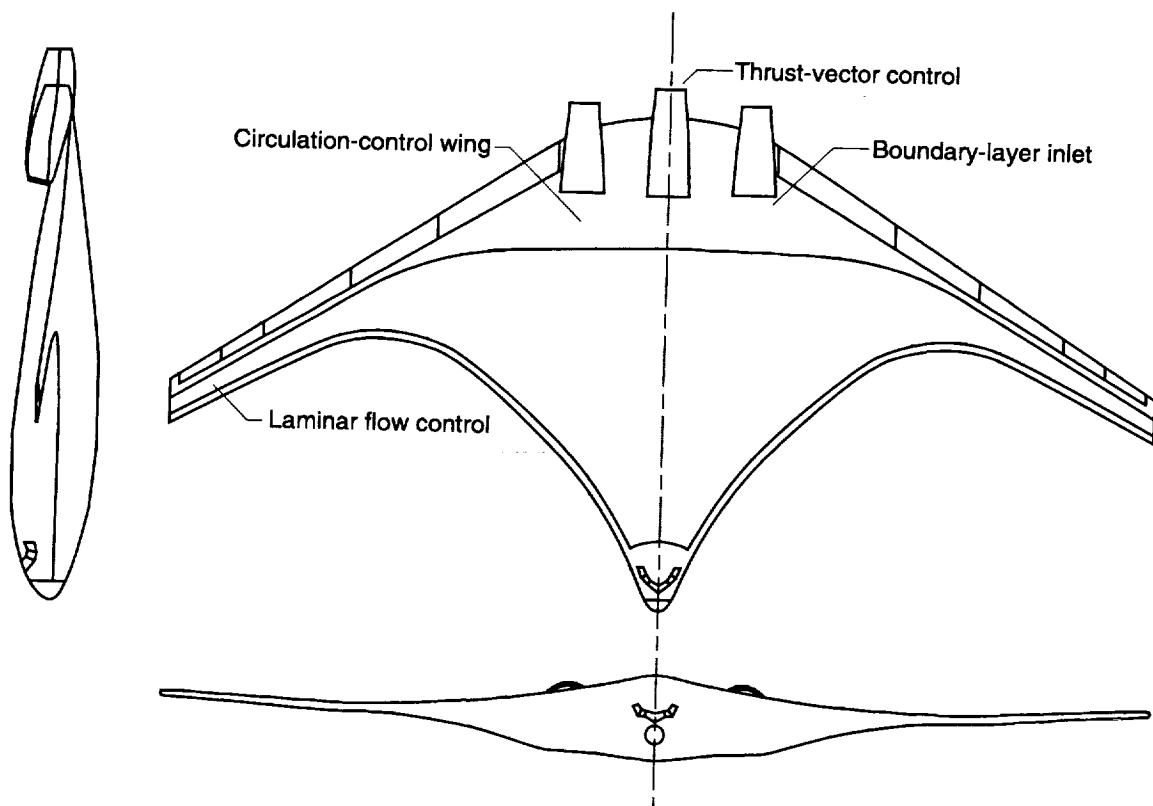


Figure 2. Blended, forward-swept-wing body concept orthographic three-view drawing.

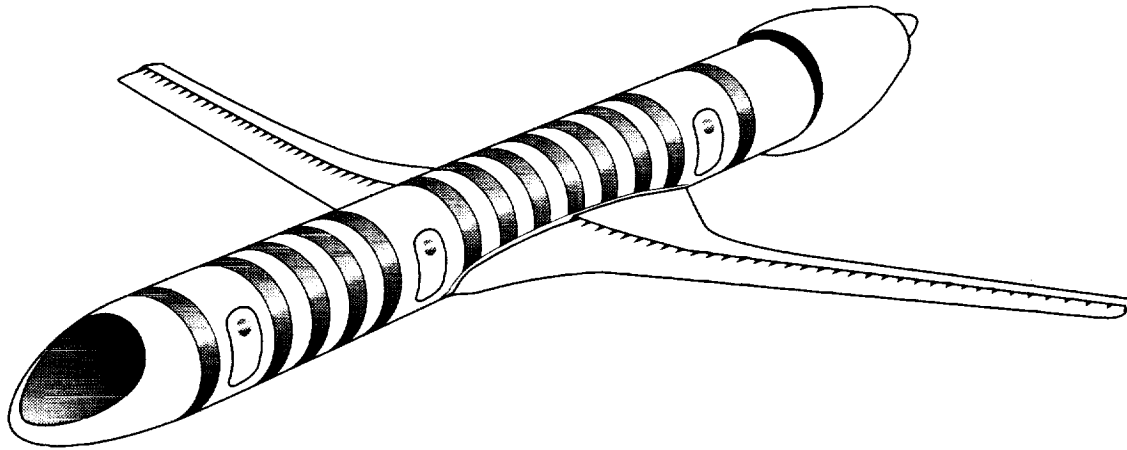


Figure 3. Distributed engine regional STOL concept perspective drawing.

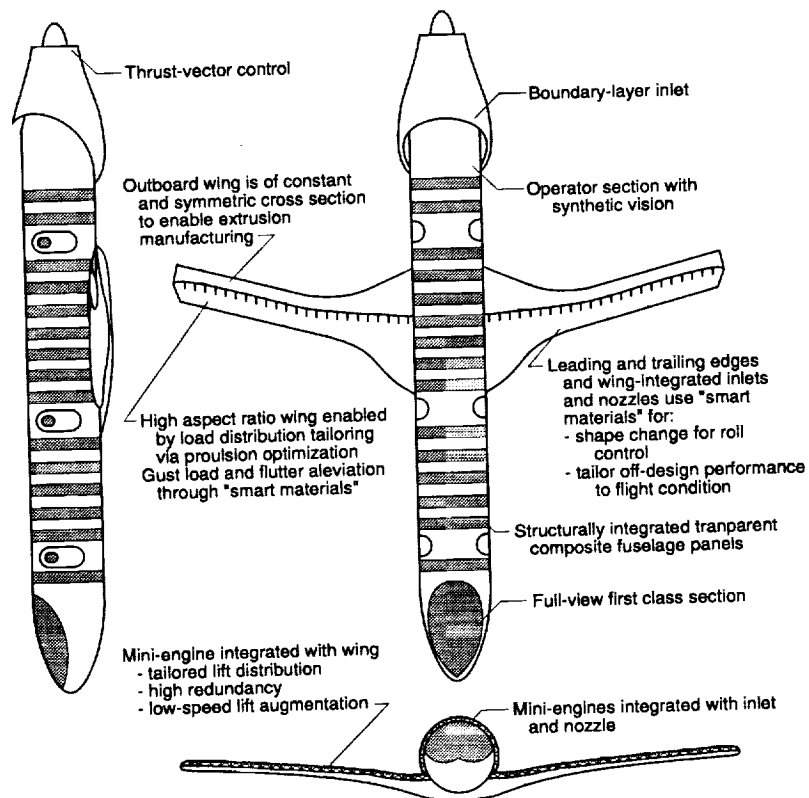


Figure 4. Distributed engine regional STOL concept three-view orthographic drawing.

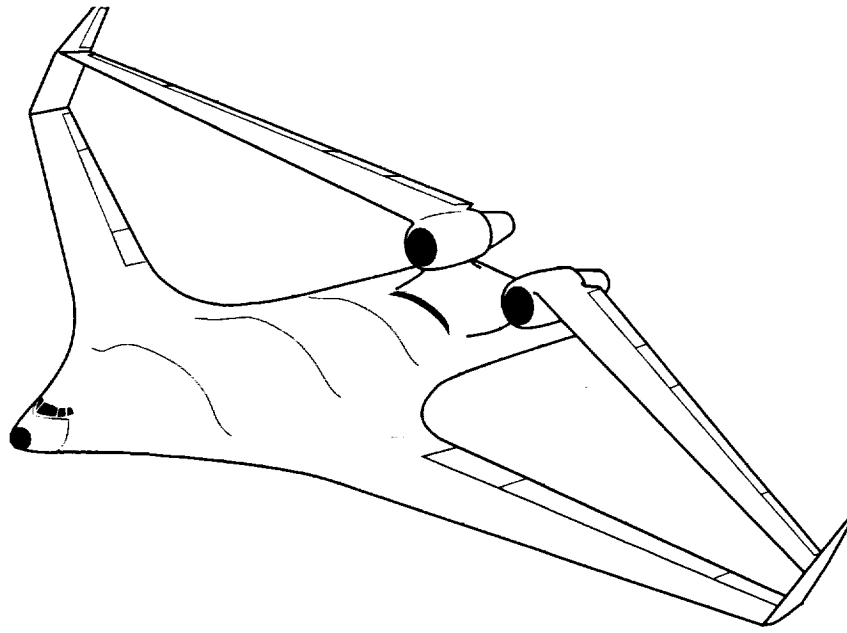


Figure 5. Goldschmied blended joined wing concept perspective drawing.

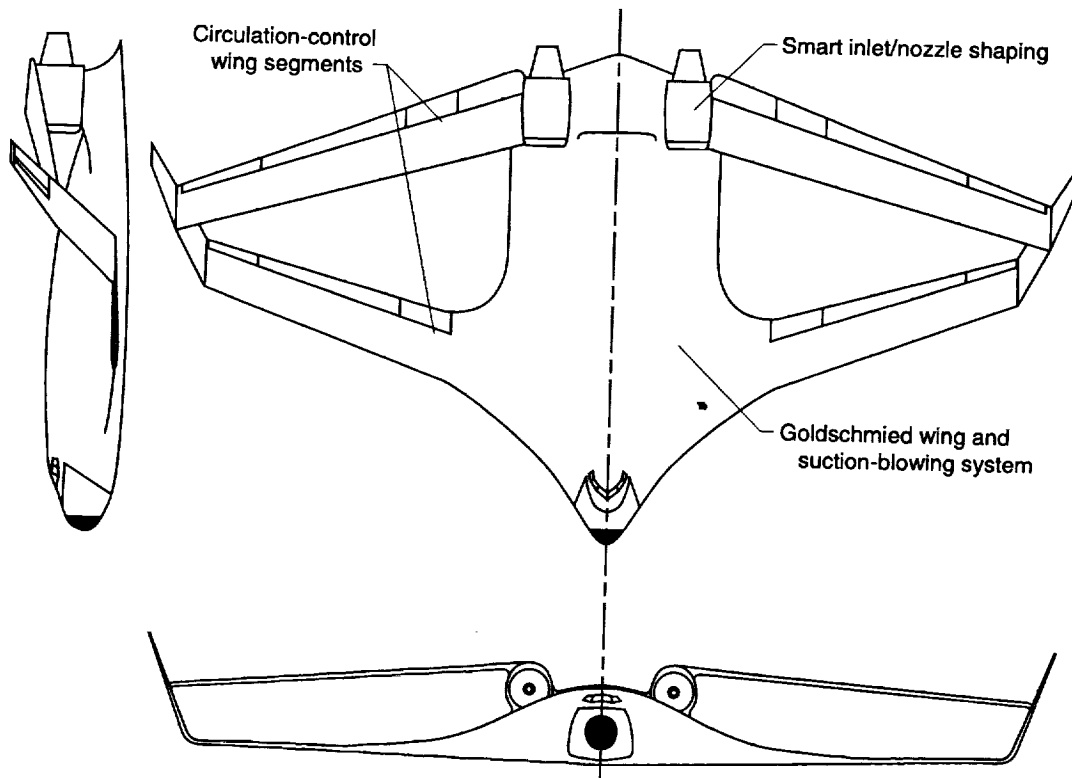


Figure 6. Goldschmied blended joined wing concept three-view orthographic drawing.

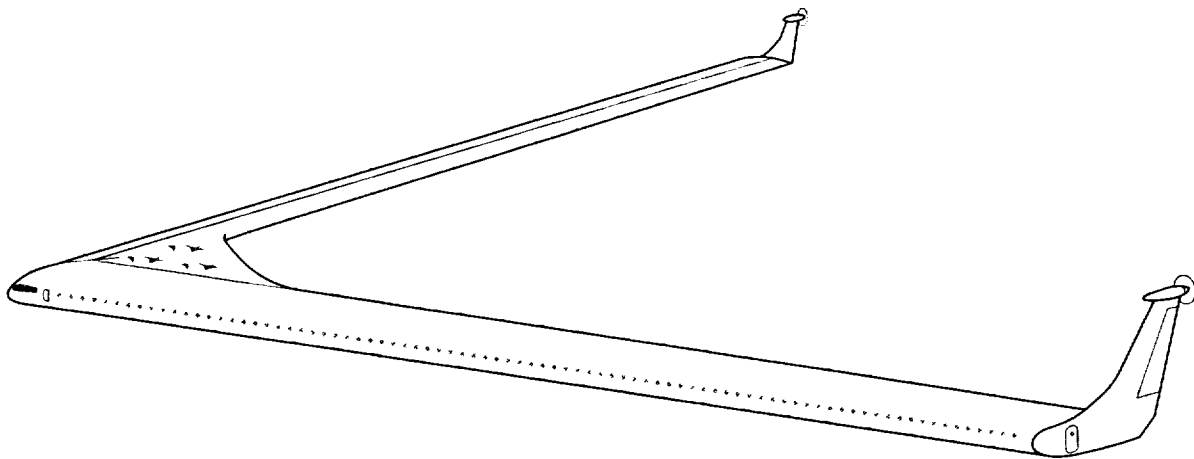


Figure 7. Modified Chaplin V-wing concept perspective drawing.

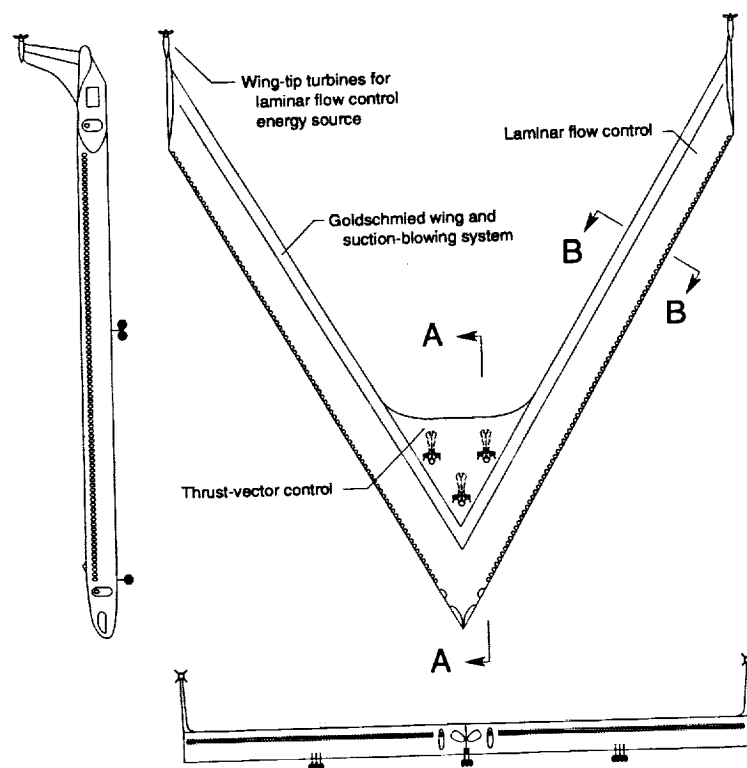
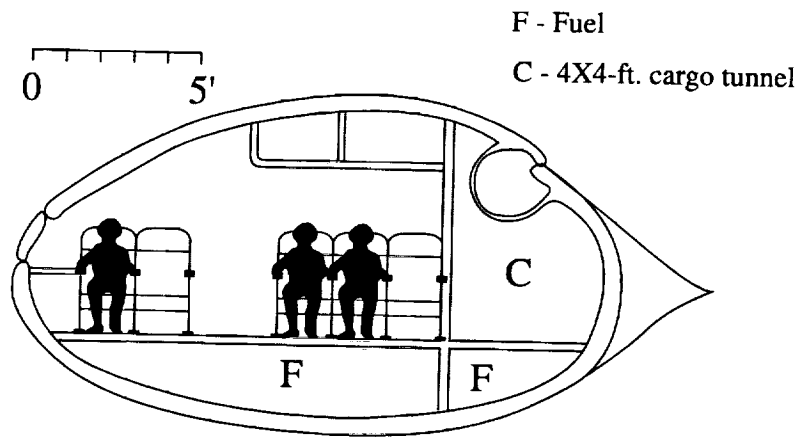


Figure 8. Modified Chaplin V-wing concept three-view orthographic drawing.



Section B-B

Streamwise cross section



Section A-A

Crossflow section

Figure 9. Cross-section details of the Modified Chaplin V-wing concept. (See fig. 8 for section lines.)

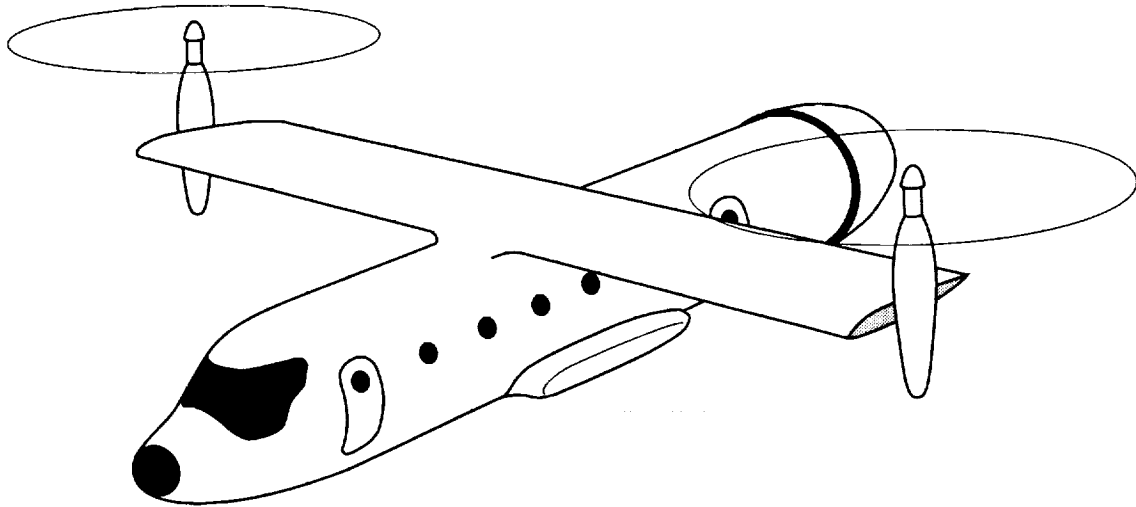


Figure 10. SnAPII civil tilt-rotor concept at 2025, version 1 perspective drawing.

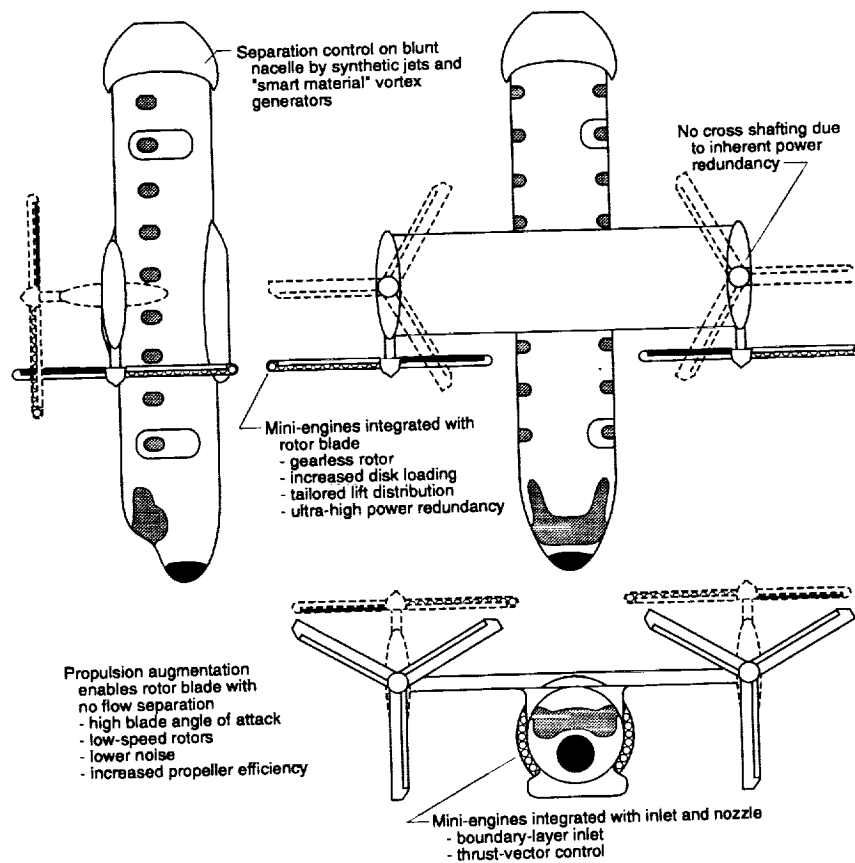


Figure 11. SnAPII civil tilt-rotor concept at 2025, version 1 three-view orthographic drawing.

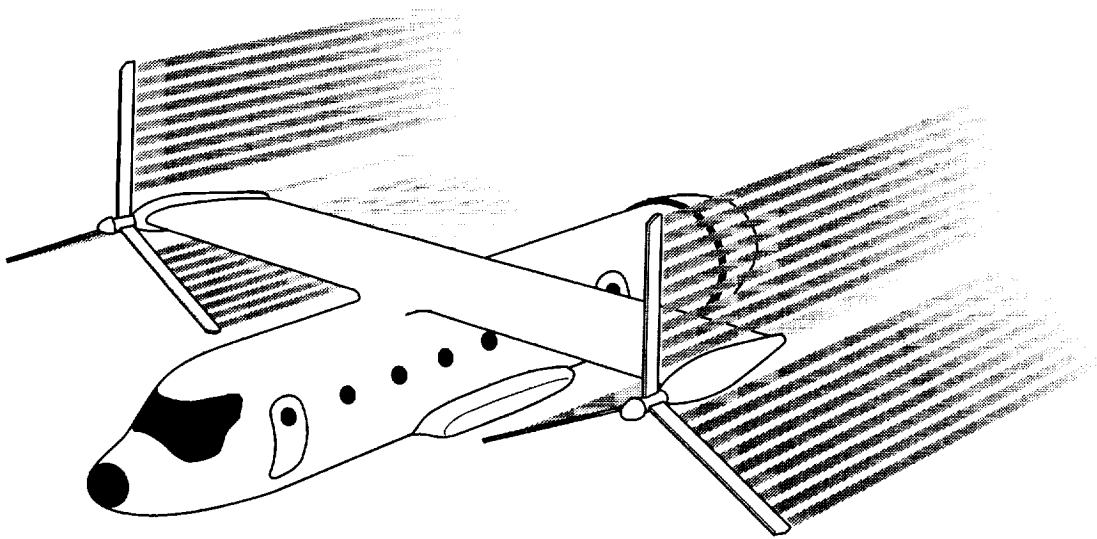


Figure 12. SnAPII civil tilt-rotor concept at 2025, version 2 perspective drawing.

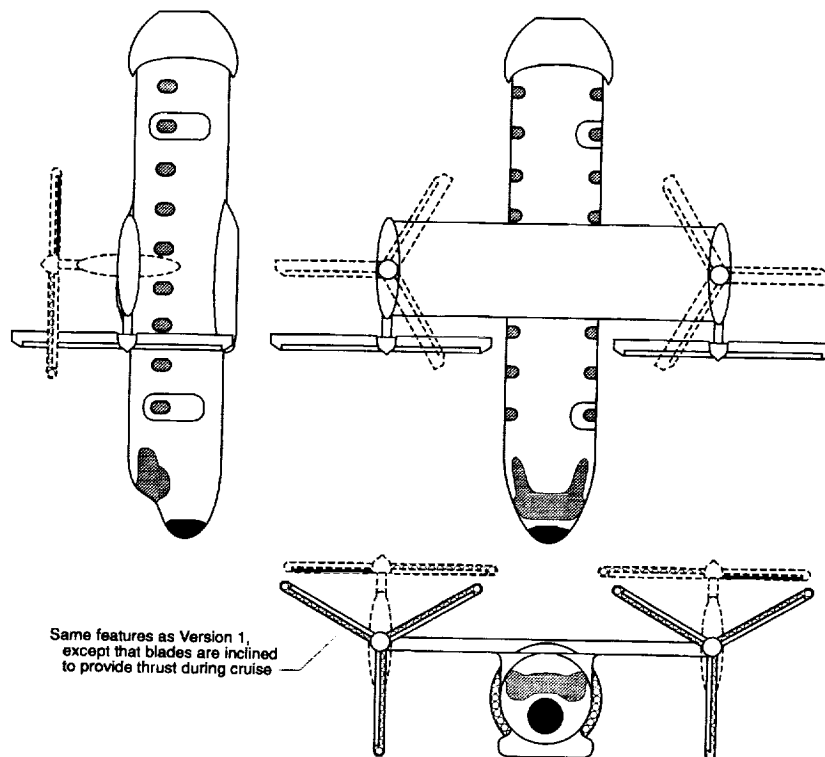


Figure 13. SnAPII civil tilt-rotor concept at 2025, version 2 three-view orthographic drawing.

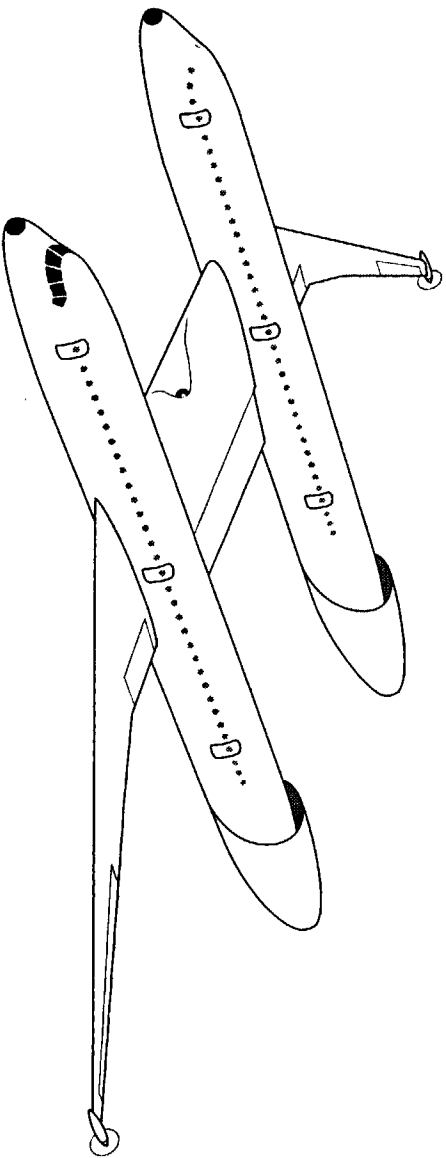


Figure 14. SnAPII twin fuselage concept, version 1 perspective drawing

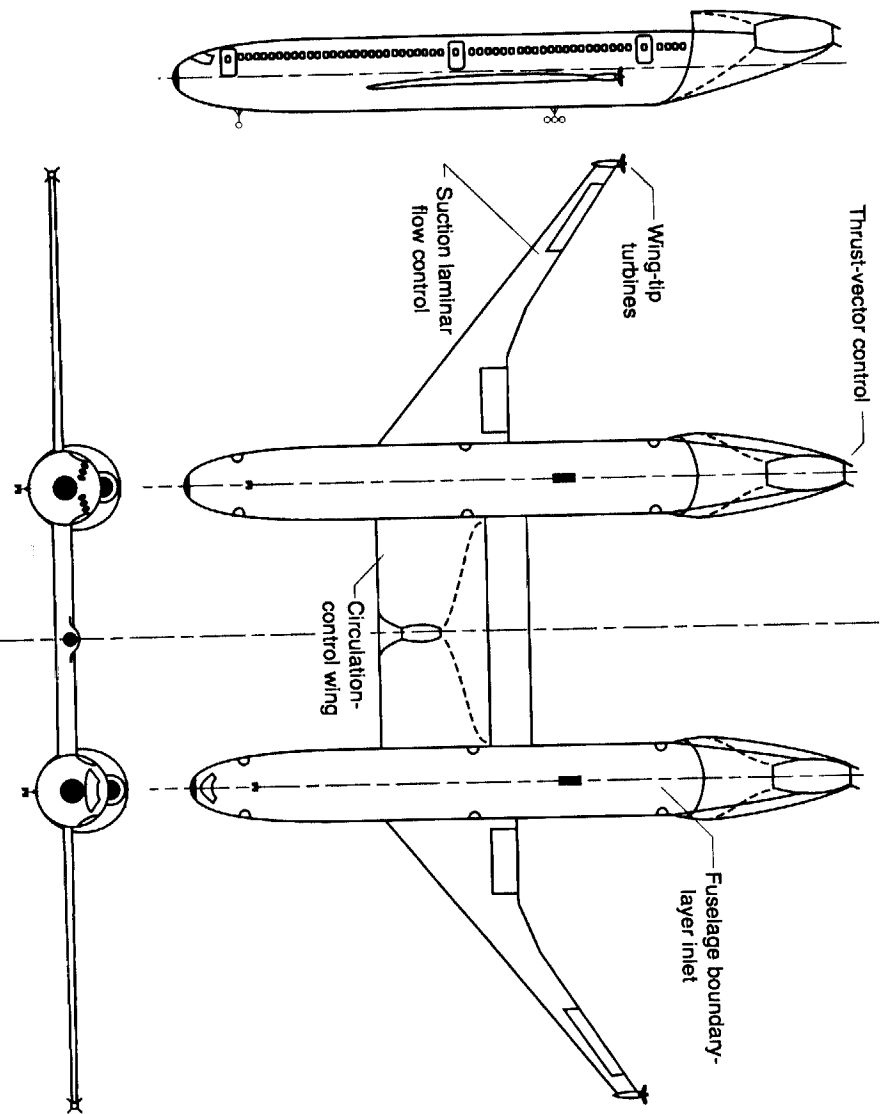
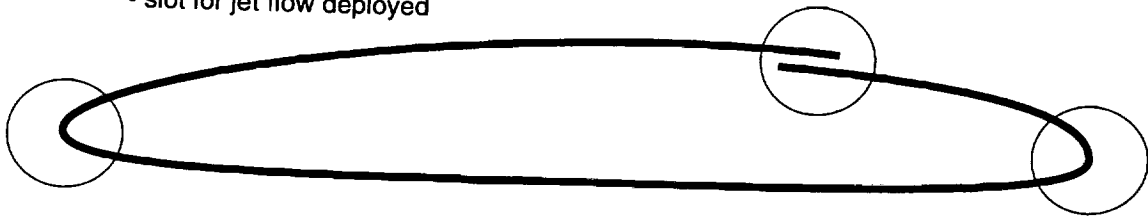


Figure 15. SnAPII twin fuselage concept, version 1 three-view orthographic drawing.

Take off and landing shape, circulation control employed

- blunt leading and trailing edges
- slot for jet flow deployed



Cruise shape, no circulation control

- leading and trailing edges morphed for efficient aerodynamics
- slot for jet flow closed

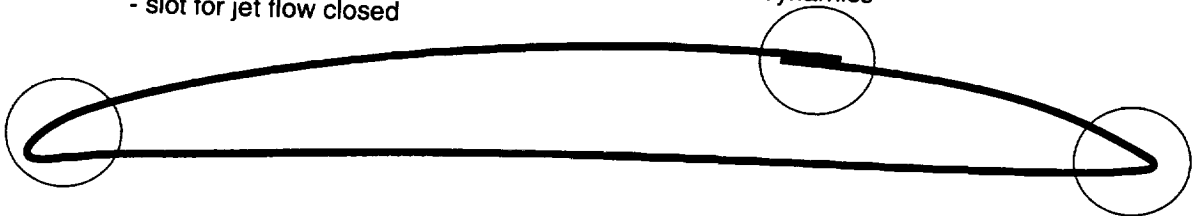


Figure 16. Circulation-control wing cross section showing areas that could be altered.

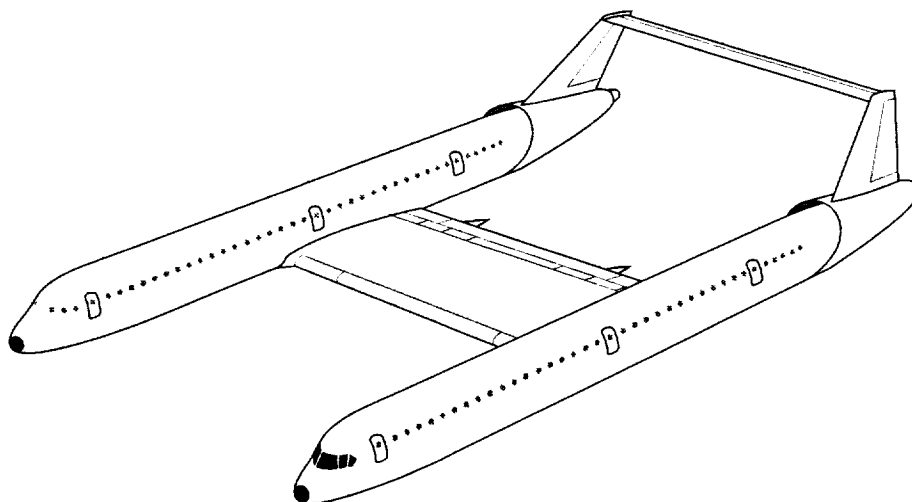


Figure 17. SnAPII twin fuselage concept, version 2 perspective drawing.

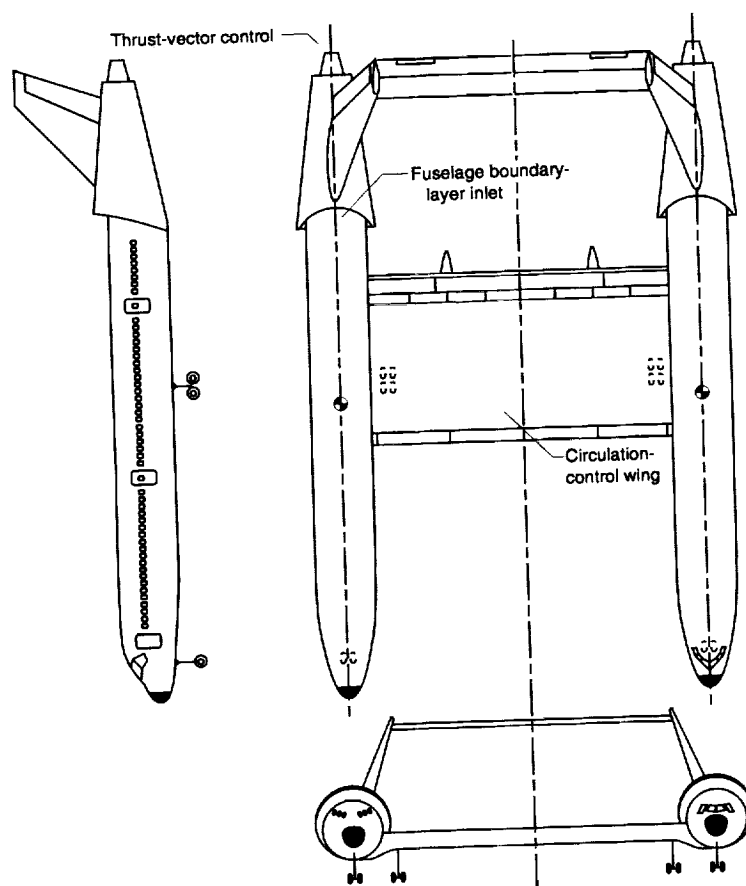


Figure 18. SnAPII twin fuselage concept, version 2 three-view orthographic drawing.

Figure 20. Trans-oceanic air-train concept three-view orthographic drawing.

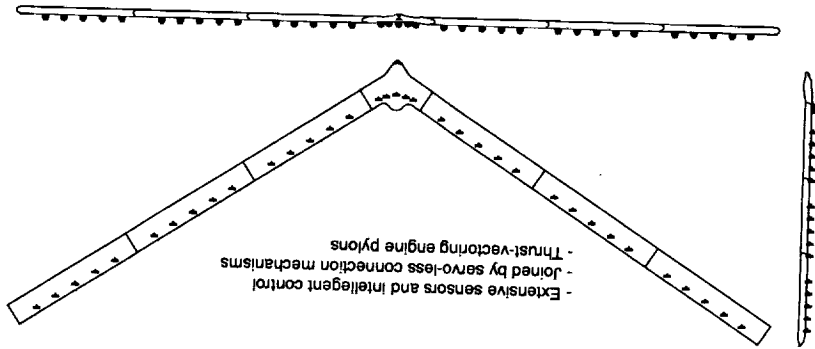
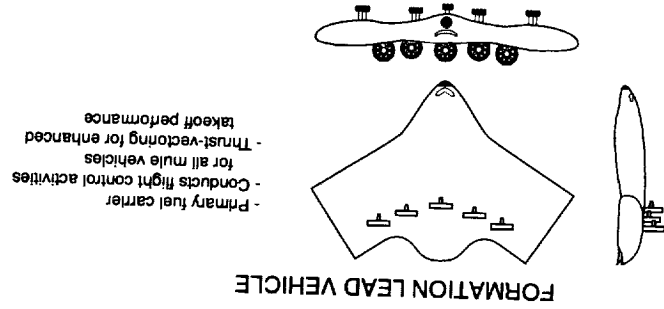
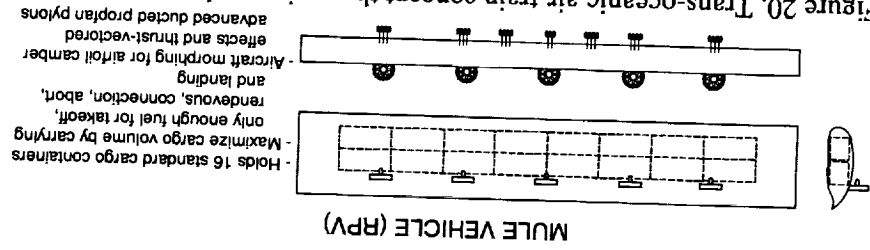
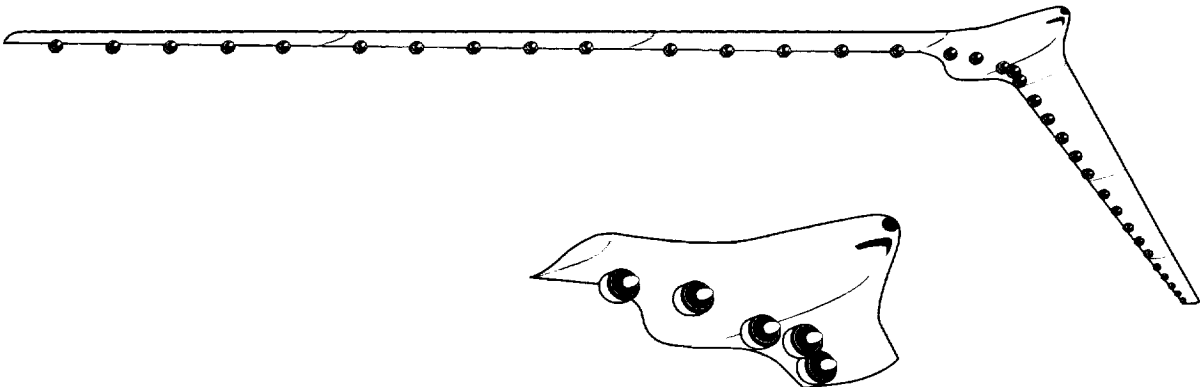


Figure 19. Trans-oceanic air-train concept perspective drawing.



Summary

This document has served to identify airframe/propulsion technologies and how beneficial interactions and integrations can result in synergistic effects. A host of technologies have been documented that use the additional energy added to the airplane system via the combustion of fuel (stored chemical energy) in the propulsion system and used in a way that provides for beneficial airframe-propulsion interactions. Other technologies that use more passive methods of extracting energy, such as wing-tip turbines, have also been documented. It is the intent of this paper to unbound the typical constraints imposed on basic performance metrics, such as high lift, cruise efficiency, and maneuver, by exploiting these technologies in a synergistic way. The documentation for each of these technologies includes a brief description of the concepts, current and/or past utilization, technology benefits, and issues for incorporating them into aircraft design.

Exploiting these propulsion/airframe integration technologies at lower speeds may lead to more efficient aircraft and/or entirely new vehicle concepts. The second part of the document addressed this in two ways. First, a synergistic application of these technologies was applied to existing aircraft concepts, one conventional (like the Boeing 777) and one unconventional (the Blended Wing-Body). Engineering estimates were then derived to provide some measure of the potential improvements by using these synergistic technologies.

Following this, an unconstrained design approach was applied using these technologies, resulting in a number of potential aircraft concepts. These concepts were weighed against the five goals of NASA's first pillar for aeronautics and space transportation success: "for U. S. leadership in the global aircraft market through safer, cleaner, quieter, and more affordable air travel." No detailed analyses were performed on these concepts; the intent was to create concepts definitions using the knowledge gained in the previous parts of the paper and the synergistic use of these technologies.

Recommendations

The following recommendations are made to continue the work initiated in this document:

(1) Based upon the evaluation presented herein of the potential benefits of applying SnAPII technologies in achieving the Agency's aeronautics goals, we recommend that system studies be initiated to independently assess our findings and perhaps provide the basis for future research in the SnAPII arena to be incorporated into new and existing programs. Those concepts that successfully pass the systems analyses could also be reasonable candidates for small-scale flight testing.

(2) Notwithstanding recommendation number one, it is recommend that all future systems studies in aeronautics consider the application of SnAPII technologies (identified in the first part of this paper), in addition to the technologies currently funded in the aeronautics program for the evaluation of system benefits. This is an appropriate time to re-look at these with advancements in such areas as computational fluid dynamics, materials, manufacturing, as well as new methods to further optimize these technologies. Furthermore, many of these technologies have been adequately tested in wind tunnel settings, but lack flight test verification. Remotely-piloted small-scale flight testing could conceivably be utilized to provide data for these technologies in a flight airframe system to reduce risk and bring them to a higher level of application readiness.

(3) The idea of investigating a combined propulsion/airframe design using a minimum entropy production method may be a good analytical approach, complementing the systems analyses and experimental studies, to exploiting SnAPII technologies. Presently, this method has been applied to only aerodynamic drag-reduction problems, but extending this to SnAPII is a next logical step.

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13. ABSTRACT (Maximum 200 words) This white paper addresses the subject of Synergistic Airframe-Propulsion interactions and integrations (SnAPII). The benefits of SnAPII have not been as extensively explored. This is due primarily to the separateness of design process for airframes and propulsion systems, with only unfavorable interactions addressed. The question 'How to design these two systems in such a way that the airframe needs the propulsion and the propulsion needs the airframe?' is the fundamental issue addressed in this paper. Successful solutions to this issue depend on appropriate technology ideas. This paper first details some ten technologies that have yet to make it to commercial products (with limited exceptions) and that could be utilized in a synergistic manner. Then these technologies, either alone or in combination, are applied to both a conventional twin-engine transonic transport and to an unconventional transport, the Blended Wing Body. Lastly, combinations of these technologies are applied to configuration concepts to assess the possibilities of success relative to five of the ten NASA aeronautics goals. These assessments are subjective, but they point the way in which the applied technologies could work together for some break-through benefits.				
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